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A preliminary study of heat strain using modelling and simulation

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Abstract

This assessment of intermittent work in hot environments was conducted to demonstrate the usefulness of modelling and simulation to the Canadian Forces. Analytical predictions of work and rest durations were made using a thermal physiology model and a human performance modelling tool, IPME. The results indicate that current guidelines could be extended to cover work in more extreme climatic conditions, including WBGT(C) values into the mid 40s, and that the published CF work and rest durations may be too conservative in some conditions. The available time for this study did not permit validation of the predictions by empirical studies, but an approach is presented for a more comprehensive investigation that would lead to a validated update to the current guidelines for commanders.

Résumé

Cette évaluation du travail intermittent dans un milieu chaud a été effectuée pour démontrer aux Forces canadiennes l'utilité de la modélisation et simulation (M et S). Des prédictions analytiques des durées de travail et de repos ont été faites à l'aide d'un modèle de physiologie thermique et d'un outil de modélisation de la performance humaine, l'Environnement intégré de modélisation de la performance (IPME). Les résultats indiquent que les directives actuelles pourraient être élargies pour inclure le travail effectué dans des conditions climatiques extrêmes, notamment à des températures d'environ 45 ^{o}C (WBGT), et que les durées de travail et de repos publiées par les FC pourraient être prudentes dans certaines conditions. Le temps alloué pour cette étude n'a pas permis de valider les prédictions par des études concrètes, mais une méthode est proposée en vue d'une étude plus approfondie qui permettrait d'obtenir une mise à jour validée des directives actuelles données aux commandants.

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Executive summary

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Cain, B.; DRDC Toronto TR 2005-255; Defence R&D Canada – Toronto; May 2006.

The purposes of this study was to assemble the tools necessary to assess the problem of work scheduling in hot climates and demonstrate their potential, and thereby the potential of M&S, for solving human factors problems faced by the Canadian Forces (CF). Time and resources were not sufficient to provide a complete solution.

Modelling and simulation provides a complementary approach to empirical studies, often allowing more extensive and cost effective analyses to be conducted quickly. Proper use of modelling and simulation draws on extensive empirical foundations whenever feasible and the current study only partially fulfills this criterion. This study makes an initial exploration of the problem, identifies shortfalls of the current study, reports lessons learned, and points out an approach for a more complete solution that builds on the current work.

As background, the Canadian Forces are being deployed more frequently to operations in equatorial regions around the world yet current guidance for working in hot environments was intended for more temperate summer climates typical of Canada and Europe. Additional guidance is required to extend current safe work schedules for hot environments and to document the associated risks with violating such guidelines when operational requirements take precedence. Military personnel face a number of risks that must be balanced and heat strain is only one of those factors that must be considered.

There is mounting evidence that working in hot environments leads to increased reaction times, decreased vigilance, and increased errors both in choice-reaction time as well as complex mental reasoning tasks, elements found in many military tasks or occupations. Although there is still debate about the causal variables that lead to these performance decrements, core temperature, rate of change of core temperature and dehydration are the leading contenders.

This study manipulated environmental conditions (summarized as a Wet Bulb Globe Temperature, WBGT(C) index ranging from 23 to 45). The environmental conditions in the analysis were selected to give WBGT values that were similar to published CF and US guidelines to assist comparison with current recommended work and rest durations. Metabolic work rates were similarly selected, although neither the WBGT nor the metabolic rates matched exactly. No empirical validation was conducted and the predicted acceptable work and rest intervals should not be used without such validation. Further, no independent validation of the thermoregulatory model was conducted; validation was only performed by the creators of the model.

Calculations of work and rest durations based on continuous work analyses were found to be too liberal and failed to consider excursions during the working phase beyond the safe core temperature. In the study of intermittent work, more than one set of work and rest conditions was often found to satisfy the safe working criteria while maximizing the amount of work done in a

work and rest cycle. Some combinations allowed longer work durations, but the resulting average amount of work done in each work and rest cycle was lower.

The safe work and rest durations selected from this study were compared with those published in the US and CF guidelines, although each of the studies have different conditions making direct comparison imprecise. Generally, the results of this study are less restrictive at low work rates, allowing longer work or shorter rest durations, and more restrictive at high work rates, requiring shorter work or longer rest durations, than the current CF guideline; the work durations were typically longer than the US guideline. These differences can be attributed to a number of factors related to interpretation but there is also the risk that the analytical results of this study are in error. The similarities with these three sets of data are encouraging, but should not be considered a replacement for scientifically sound empirical validation.

These results do suggest that the current CF guidelines are too restrictive and that their underlying assumptions should be reassessed. Additional results indicate that some work and rest cycles were feasible in conditions that were well beyond the CF guidelines, even in WBGT(C) conditions in excess of 40. This suggests that current guidelines should be extended to cover more adverse environmental conditions that can be experienced by military personnel operating in hot, humid climates.

The number of important factors and the range of values that need to be considered make empirical studies impracticable. The analytical, modelling and simulation approach seems to be the only viable solution to problems such as this, yet it should not be applied without empirical support for model development and validation as spot checks on the accuracy of the results.

Sommaire

A preliminary study of heat strain using modelling and simulation

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Le but de cette étude était de rassembler les outils nécessaires pour évaluer le problème de l'établissement d'un horaire de travail dans les climats chauds et de démontrer leur potentiel, et par conséquent le potentiel de la M et S, pour la résolution de problèmes liés aux facteurs humains que rencontrent les Forces canadiennes. Les ressources et le temps alloués n'étaient pas suffisants pour arriver à une solution complète.

La modélisation et simulation fournit une méthode complémentaire aux études concrètes, et elle permet souvent des analyses plus approfondies et plus économiques, qui sont effectuées rapidement. Une utilisation appropriée de la modélisation et simulation se fonde sur des études concrètes approfondies lorsque cela est faisable, et la présente étude ne respecte ce critère que partiellement. Cette étude fait une exploration initiale du problème, détermine les lacunes de l'étude actuelle, indique les leçons retenues et présente une méthode pour arriver à une solution complète qui se fonde sur le travail actuel.

La réalisation de cette étude s'explique par le fait que les Forces canadiennes sont plus fréquemment déployées dans le cadre d'opérations dans des régions équatoriales partout dans le monde, alors que les directives actuelles de travail dans un environnement chaud concernent des climats d'été tempérés qui caractérisent le Canada et l'Europe. Des directives supplémentaires sont nécessaires pour permettre l'établissement d'un horaire de travail sécuritaire dans des environnements chauds et pour documenter les risques liés au non respect de ces directives lorsque des exigences opérationnelles s'imposent. Le personnel militaire est confronté à un certain nombre de risques qui doivent être réduits, et la fatigue due à la chaleur n'est que l'un des facteurs qui doivent être examinés.

De plus en plus de données prouvent que le travail dans un environnement chaud entraîne des temps de réaction plus grands, une vigilance amoindrie et une augmentation des erreurs autant dans le temps de réaction de choix que dans les tâches nécessitant un raisonnement mental complexe, éléments que l'on rencontre dans bon nombre de tâches et de professions militaires. Bien qu'il y ait encore des discussions quant aux variables causales qui sont à l'origine de cette diminution de performance, la température centrale, le rythme de changement de la température centrale et la désydratation en sont les principales causes.

Cette étude a traité des conditions environnementales (résumées comme un indice de température variant entre 23 et 45 ^{o}C [WBGT]). Les conditions environnementales de l'analyse ont été choisies de façon à avoir des valeurs WBGT semblables à celles qui sont publiées dans les directives des FC et des USA, pour faciliter la comparaison avec les durées actuelles de travail et de repos. Les rythmes de travail métaboliques ont été choisis de façon similaire, bien que ni les valeurs WBGT ni les taux métaboliques ne coïncident exactement. Aucune validation concrète n'a été effectuée, et les intervalles acceptables de travail et de repos prévus ne devraient pas être

utilisés avant d’être validés. De plus, aucune validation indépendante du modèle de thermorégulation n’a été effectuée; la validation n’a été effectuée que par les auteurs du modèle.

Les calculs des durées de travail et de repos basés sur des analyses de travail continu ont été jugés trop approximatifs et ils n’ont pas tenu compte des cas où, pendant la période de travail, la température ambiante dépasse la température centrale sécuritaire. Dans l’étude sur le travail intermittent, différents ensembles de conditions de travail et de repos ont souvent été jugés comme satisfaisant les critères de travail sécuritaire, tout en maximisant la quantité de travail effectué dans un cycle repos-travail. Quelques combinaisons ont permis de plus longues durées de travail, mais le total de la quantité de travail moyenne dans chaque cycle travail-repos était plus bas.

Les durées de travail et de repos sécuritaires retenues de cette étude ont été comparées avec celles qui ont été publiées dans les directives des États-Unis et des FC, bien que chacune des études aient des conditions différentes, ce qui rend imprécise une comparaison directe. En général, les résultats de cette étude sont moins restrictifs pour des rythmes de travail bas comportant des durées de travail plus longues ou des durées de repos plus courtes, et plus restrictifs pour des rythmes de travail plus élevés, exigeant des durées de travail plus courtes ou des durées de repos plus longues, par rapport aux directives canadiennes actuelles; les durées de travail étaient généralement plus longues que celles prévues par les directives des États-Unis. Ces différences sont attribuables à un certain nombre de facteurs liés à l’interprétation, mais il y a aussi le risque que les résultats analytiques de l’étude soient erronés. Les similarités entre ces trois ensembles de données sont encourageantes, mais elles ne doivent pas être considérées comme un substitut à une validation concrète scientifique en bonne et due forme.

Ces résultats donnent à penser que les directives actuelles des FC sont trop restrictives et que les hypothèses qui les sous-tendent devraient être réévaluées. D’autres résultats indiquent que certains ratios travail-repos étaient réalisables dans des conditions dépassant largement celles prévues par les directives des FC, même dans des conditions excédant une température de 40 ^{o}C (WBGT). Ceci tend à indiquer que les directives actuelles devraient être élargies pour inclure des conditions environnementales plus malsaines auxquelles peut faire face le personnel militaire opérant dans des climats chauds et humides.

Le nombre de facteurs importants et la gamme de valeurs dont on doit tenir compte font qu’il est impossible d’effectuer des études concrètes. La méthode fondée sur l’analyse et la modélisation et simulation semble constituer la seule solution viable à de tels problèmes, bien que celle-ci ne devrait pas être mise en application sans être appuyée par des études concrètes en vue de l’élaboration et de la validation d’un modèle, à titre de vérifications ponctuelles de l’exactitude des résultats.

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Introduction

The Canadian Forces are being deployed more frequently to operations in hot environments around the world. Current guidance for working in hot environments was intended for more temperate climates typical of Canada and Europe. Peace keeping and humanitarian aid deployments to the Middle East, Afghanistan, Haiti and Singapore are likely to experience adverse environments more typical of equatorial climates (NATO A1-A2 and B1-B2 (1990, pp486-493)), requiring additional guidance for safe work schedules and the health risks associated with violating such guidelines.

Considerable empirical and analytical work on the effects of heat stress has been conducted by TTCP and NATO RTO nations that can be used to provide some of the needed guidance. These data provide a rich body of corporate knowledge that can be incorporated into modelling and simulation (M&S) of human factors problems and performance prediction.

Modelling and simulation provides a complementary approach to empirical studies, often allowing more extensive and cost effective analyses to be conducted quickly, but still requiring validation from the empirical human sciences. In return, an empirical approach can benefit from analytical studies to identify areas of study that would be appropriate for study to best apply limited laboratory resources. As our understanding of human factors increases, such as the effects of heat strain on performance, analytical models will become increasingly useful to military analysts to assess the sensitivity of other analyses to the capabilities and limitations of the human operator.

Purpose

The purposes of this study were to assemble the tools necessary to assess the problem of work scheduling in hot climates and demonstrate their potential, and thereby the potential of M&S, for solving human factors problems faced by the Canadian Forces.

It was not the intent to provide a complete solution to scheduling problems associated with working in hot environments; the time and resources were not sufficient for that task. Rather, this study was to make an initial exploration of the problem, identify shortfalls of the current study, report lessons learned, and point out an approach for a more complete solution that builds on the current work.

Background

Froom et al. (1993) reviewed 500 helicopter accidents and incidents that had been attributed to pilot error. Heat stress due to increased dry bulb and wet bulb temperatures correlated with an increase in the number of errors that were likely to be committed. When the dry bulb temperature exceeded 35°C, pilots were 6 times more likely than average to commit errors; between 30 and 34°C, there is a 50% increase in errors from the average. When the wet bulb temperature was in the range of 24°C to 26°C, the error rate was 20% to 70% greater than average. Froom et al. note that while there are several confounding factors, the pilot errors occurred at an environmental heat stress that resulted in a physiological heat strain that while uncomfortable, was tolerable and well below the level of collapse.

Lieberman (2005) was able to study the effect of a number of concurrent stressors on cognitive performance and mood during an intense military training exercise over three days. Soldiers experience severe sleep loss, under nutrition, dehydration and physical exertion. All cognitive tests indicated significant degradation in performance after one day of the trial although testing of

militarily relevant tasks embedded in the exercise was not feasible. The performance decrement observed during the trial (~20% in all measures) seemed greater than that due to any single stressor (<7%), based on laboratory observations suggesting that the effects of the stressors are at least additive and possibly interacting. Reaction time increased, vigilance decreased and errors in choice reaction time tasks increased as the exercise progressed. Field studies such as this are key components for extending laboratory and theoretically based evaluations of the effects of individual stressors to the more complex operational scenario where military personnel face a multitude of stressors.

Johnson and Kolbrick (2001) indicate that continuous repetitive tasks that are boring tended to be affected most by stressful environments. They note that the role of heat induced changes in performance is difficult to predict from the literature because of contradictory results arising from differences in methodology. The go on to say that there is, however, considerable support for the idea that thermal stress impairs complex mental performance. Thermal strain is often accompanied by increased errors of omission rather than errors of commission (forgetting to do something rather than doing something poorly) as well as other effects such as a narrowing of attention (potentially leading to poor situation awareness). They postulate that thermal stress affects performance through 3 principal mechanisms: arousal, changing deep body temperature, and emotional affect changes. The effects of changes in arousal often follow an inverted U relationship but they are also moderated by other factors such as expertise leading to contradictory results between individuals or between studies. Hancock and Vasmatzidis (2003) propose that it is the stress of a dynamically changing deep body temperature rather than a specific steady state value that leads to a division of attention, resulting in decreased performance. When thermal stress reacts with other context stressors such as threats to safety, a further tunnelling of attention created by changes in emotional factors could lead to additional errors of omission but reasoning and problem solving may also suffer.

Johnson and Kobrick summarize their review of the importance of thermal stress and strain to military performance noting

1. Tasks involving support actions such as straightforward target detection are largely unaffected. Simple tasks such as button pressing, well rehearsed activities or even simple discriminations (such as friend-foe identification) should show little degradation. More complex reactions involving reasoning and multiple-choice can be expected to degrade significantly, showing increasing decision time as thermal stress and hence strain increase to the point of physiological collapse. Heat acclimatization should mitigate some of the effects.

2. Visual perception is unlikely to be affected directly.

3. Routine vigilance and attention will be severely degraded by heat stress yet these same factors will likely be unaffected by acute events that increase arousal, temporarily offsetting the debilitating effects of thermal strain.

4. Thermal stress has been shown to degrade short-term memory, mathematical reasoning, map plotting and the coding or decoding of messages. Acclimatization and extensive training to make activities largely automatic are required to mitigate these effects.

5. Manual dexterity, steadiness and tracking performance all degrade as thermal stress increases.

6. The ability to perform several concurrent tasks adequately will be compromised by thermal stress.

7. Effects will depend upon the time on task, motivation, level of expertise, level of acclimatization, and operator state prior to exposure.

Buono & Sjoholm (1988, eq.9, p172) report that physically-fit men and women have maximal sweat rates that are more that twice that of sedentary individuals (approximately 6.5 g/m^2min versus 3 g/m^2min), although sweat rates did not differ between men and women. They reported a linear relationship between sweat rate (g/m^2min) and $V0_2Max$ (ml/kg min) of $0.16V0_2Max – 3.16$, although the correlation was only moderate (r=0.73). Their conclusion was that training (and, by inference, acclimatization) in the stressful environment and increased fitness affect local sweat production independent of the central sweating drive. This allows exposed personnel to tolerate thermally stressful conditions more effectively than their sedentary counterparts, supporting Johnson and Kobrik's observations, and providing evidence for the importance of advanced preparations for operations in hot climates.

While working in hot environments has an associated risk, military personnel face a number of risks that must be balanced. The approach typically adopted for mitigating risks associated with thermal stress is to adopt work and rest intervals according to the severity of the stress. Establishing appropriate intervals depends on a number of factors and Table 1 lists some that can affect performance when working in hot environments. Each factor will have a range of values relevant to military activities and assessment of the effect of each factor at a representative number of levels is daunting; the combination of relevant environmental factors alone at a moderate level of resolution could result in 1000 different conditions. When combined with personal factors as well as task factors, the number of conditions to be assessed to provide guidance on how long to work, or how hard to work, the number of unique conditions spanning the range of relevant factors could easily exceed 100,000 even with judicious selection. Such an assessment for even a modest level of completeness is impracticable for human trials and very expensive even for simulation.

Table 1. Some of the factors that can affect performance during work in hot environments.

Personal factors	Environmental factors	Task factors
Metabolic rate	Dry bulb temperature	Physical demand (through metabolic rate)
Body weight	Water vapour pressure (relative humidity, wet bulb temperature)	Work interval duration
Body fat	Radiant temperature	Rest/Work ratio
Fitness (VO_2 Max)	Solar radiation	Work day length
Acclimatization	Wind speed	Health risk tolerance
Clothing water vapour permeability	Compensable versus Uncompensable heat stress	Cognitive demands
Clothing thermal insulation		Consequences of error
Hydration status		
Initial core temperature		

Studies of people working in hot environments have been ongoing within numerous military and civilian research centres for many years. While much is known about the physiological responses to hot environments, less is known about the effects of thermal strain on mental performance. There are a number of thermal physiological models that predict physiological changes due to external stressors, but there is little guidance as to what level of detail is required for assessing risks associated with military activities in hot weather. Since the risk of providing inappropriate guidance to military personnel for working in hot environments is that their health and safety may be compromised, more detailed models seem warranted, although increased level of detail means increased cost of execution. As any guidance provided will be moderated both by individuals performing the work as well as their commanders, it seems plausible that moderately detailed thermal physiology models might suffice, balancing cost and accuracy.

Heat stress measurement

It is difficult for commanders in the field to know in detail how environmental conditions and task demands affect mental and physiological state for exposed personnel, and then how the operator state affects both task performance and health concerns. Brake and Bates (2002) note there have been in excess of 60 heat stress indices developed over the last century to characterize the thermal stress imposed by the environment and no single index that adequately reflects the resulting thermal strain has been universally accepted.

Empirical indices, generally expressed in terms of environmental, meteorological parameters (such as dry-bulb temperature, humidity, and solar radiation), or derivations based on them (such as

Equivalent Temperature and Wet Bulb Globe Temperature, WBGT). These are readily measured or derived in the field, providing an estimate of the severity of the environmental conditions that can be compared against tabulated criteria for safe exposures. There are several complicating factors with using these indices. The indices typically only characterize the environment and seldom account for the type of work being performed, the clothing worn, or the fitness and acclimatization of the individuals working in that environment; the additional factors must be considered in the guidelines themselves. Further, significant changes to factors associated with the heat stress-performance relationship require complete reassessment. Thus, the usefulness of any of the indices is dependent on appropriate interpretation within the current operational context by commanders. The issue then is to establish appropriate criteria by which to assess the significance of the heat stress index being used.

Rational indices are those that are based on physiological responses to exposure, such as sweat rates and core temperature changes. These reflect the strain of the operator due both to exposure to the environment and the task being performed. While such parameters are readily measured in the laboratory, field measurement is more difficult and perhaps inappropriate for operational activities. The role of these variables is to relate performance criteria (such as task performance or personal health risks) back to the causal factors reflected in the empirical indices and the tasks. With rational indices, significant changes to important variables may only require partial reassessment of the heat strain-performance relationship, saving time and effort. Rational indices often fulfil an intermediate role, providing the guidance necessary to interpret empirical indices within an operational context.

Brake and Bates (2002) note that for continuous work to be safe for the individual performing the work, the core temperature must plateau at a safe level. Even that criterion varies between published indices, with some assuming 38ºC as a safe limit and others assuming 38.5ºC. NIOSH (National Institute for Occupational Safety and Health[1]) and ACGIH (American Conference of Governmental Industrial Hygienists[2]) standards have opted for a limiting, deep body core temperature of 38ºC for continuous work and this has been extended to work/rest cycles for conditions where continuous work is not possible (Anonymous, 1998). The rationale for selecting a criterion of 38ºC appears to be largely based on considerations of the worker's personal health and safety. Unfortunately, the maximum core temperature associated with a metabolic rate for continuous work does not accommodate the fluctuating core temperatures that occur during work/rest cycles, nor does it address the effects of the rate of change of core temperature on performance as proposed by Hancock and Vasmatzidis (2003).

In their evaluation of several heat stress indices, Brake and Bates (2002) found that the predicted limiting metabolic rates varied by as much as 100 W/m^2 (or about 200W for a typical male), indicating a wide range of "acceptable" maximum activity level. They also note that several of the indices produce contradictory relationships with the independent, environmental factors, no-doubt a reflection of the various assumptions that have been embodied in the heat and moisture transfer relationships of the indices.

Brake and Bates (2002) proposed using a time-weighted mean heat balance relationship to predict the fraction of time working in a work/rest relationship as

$$T_{w\%} = 1 \Big/ \left(1 + \frac{MR_{work} - WL_{work}}{WL_{rest} - MR_{rest}}\right) \tag{1}$$

[1] http://www.cdc.gov/niosh/homepage.html
[2] http://www.acgih.org/

where *WL* is the limiting metabolic rate for continuous work under the environmental conditions for each of the *work* and *rest* phases as denoted by the corresponding subscripts, and *MR* is the actual metabolic rate during each phase. The difference between the limiting metabolic rates for *work* and *rest* in Equation 1 is to accommodate the use of shelters during the rest phase with differing environmental properties from the work environment, or any other differences between the phases such as variations in the clothing worn. As will be shown later in this report, determining a work/rest ratio is only part of the solution and the amount of time spent working in any interval is also an important factor for maintaining a safe core temperature.

Wet Bulb Globe Temperature (WBGT) Index

The Wet Bulb Globe Temperature (WBGT) Index has been adopted by the Canadian Forces as the standard assessment of environmental conditions relevant to thermal stress (D_Safe_G3, 1999).

The index is calculated from 3 temperatures when the exposure includes sunshine

$$WBGT = 0.7T_{NWB} + 0.2T_G + 0.1T_{DB} \qquad (2)$$

or from 2 temperatures when there is no direct radiative source

$$WBGT = 0.7T_{NWB} + 0.3T_G \qquad (3)$$

where T_{NWB} is the natural wet bulb temperature, $T_{\mathbf{G}}$ is the globe thermometer temperature, and T_{DB} is the dry bulb air temperature.

The WBGT is not a true thermodynamic temperature[3]. The WBGT is an index of the severity of the environment that seems to correlate sufficiently well with perceived heat strain. The WBGT, and other indices like it, seem to be confused with the dry bulb temperature by those not trained in its use, but the WBGT is typically much lower than the dry bulb temperature in dry climates because of the large weighting of the wet bulb temperature (which is typically low in dry climates.)

Originally, the WBGT was calculated using the true Wet Bulb Temperature, measured by exposing a wetted thermometer to moving air. The true Wet Bulb Temperature is a better measure of the saturation air temperature that is directly related to the amount of water vapour in the air, or relative humidity, and is more commonly used in meteorological work. The natural wet bulb temperature exposes a wetted thermometer to still air, and it is thought to better capture the thermal stress imposed on workers due to high relative humidity, which affects the ability to evaporate sweat and provide evaporative cooling. Typically, the natural wet bulb temperature is about 1.1°C higher[4] than the true Wet Bulb Temperature due to the lower evaporation rate of the natural wet bulb temperature measurement.

The globe temperature is an assessment of the radiative and convective heat transfer from the environment and here are several commercial WBGT measurement devices with various size globes. Usually globe thermometers are calibrated to represent an equivalent temperature of a blackened, 15 cm (6 inch) diameter globe thermometer, but differences in the globe temperature differences resulting from globes of different diameters has only a small effect on the WBGT index (<0.5 C for

[3] WBGT values in this report will be printed without the degrees symbol, º, to reduce the likelihood that it will be confused with an actual temperature. The values will retain the C symbol to indicate that it is composed of temperatures measured on the Celsius scale rather than the Fahrenheit temperature scale.
[4] http://www.ccohs.ca/oshanswers/phys_agents/humidex.html

most conditions). The globe temperature is also not a true thermodynamic temperature, but is an estimate of the relative contributions of thermal radiation and convective heat transfer from an unheated body.

In this study, the WBGT index was computed using meteorological, thermodynamic and engineering relationships of heat and mass transfer while manipulating basic environmental factors rather than the three temperatures noted in Equations 2 and 3. Specifically, the dry bulb temperature, the relative humidity, the wind speed, and thermal radiation were the independent environmental variables manipulated. Estimates of WBGT values and corresponding meteorological variables used in the simulations of this study can be seen in 0.

Existing guidance for working in hot environments

There are several resources on the World Wide Web concerning working in hot environments. Many of them appear to be based on recommendations of the American Congress of Government and Industrial Hygienists (ACGIH) for exposure limits (Anonymous, 1998). There are many national, provincial or state, and organizational occupational health and safety versions of these recommendations. There are often slight differences among the various guidelines and each may represent an interpretation of several sources. Unfortunately, many directives do not cite the reference data used to justify their decisions.

Countries that have equatorial territories (such as Australia) or that regularly operate in equatorial regions (such as the United States) have numerous, freely available publications with recommended work and rest durations (Anonymous, 1991a, 1991b; Reeves, 2004). A typical example abstracted from a United States Air Force pamphlet (AFMOA/SGZA, 2002) is shown in Table 2.

The Canadian Forces currently have a heat stress directive with two supporting documents concerning working in hot environments: CFAO 34-47 and CFMO 40-02. These documents outline the symptoms and treatment of heat illness as well as recommending work-rest intervals and water consumption for WBGT values between 26C and 32C, although, as with others, they do not report the rationale used in deciding on the various exposure limits. An abstraction of the Canadian Forces' guidelines for non-military activities (D_Safe_G3, 1999) is shown in Table 3. The values are similar to those of the US Air Force publication although. Despite not being adopted by the CF for military activity, these values represent a starting point for determining work-rest schedules that are unlikely to result in heat stress casualties.

Table 2. A summary table of US Air Force guidelines for work-rest intervals versus WBGT index at three total metabolic rates for whole body work. Source: (AFMOA/SGZA, 2002)

WBGT	Approximate Work and Rest duration (minutes/hour)								
	Light: 250 W			Moderate: 350 W			Heavy: 500 W		
(C)	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W
25.3	Continuous	Work	Possible				40	20	0.5
27.1				50	10	0.2	30	30	1
28.7				40	20	0.5	30	30	1
30.0				30	30	1	20	40	2
30.5	50	10	0.2	20	40	2	10	50	5

Table 3. Condensed version of current CF guidelines for working in hot environments. Source: D_Safe_G3 (1999).

WBGT	Approximate Work and Rest duration (minutes/hour)								
	Light: 370 W			Moderate: 500W			Heavy: 700W		
(C)	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W
<25.0	Continuous	Work	Possible						
26.0							45	15	0.3
28.0				45	15	0.3	30	30	1.0
29.5				30	30	1.0	15	45	3.0
31.0	45	15	0.3	15	45	3.0			
31.5	30	30	1.0						
32.0	15	45	3.0	Work	Not	Recomm	ended		

The values quoted for the total metabolic rate in many tables should not be taken too literally; they are often merely representative of a range of metabolic rates that can vary up to ±100 W. Several of the available directives[5] provide examples of how to compute the total metabolic rate for classes of tasks, but it is somewhat cumbersome for users not familiar with the field. In many cases, these examples are based on a normative model such as a 70 kg male with a body surface area of 1.8 m^2; incorporating all of the variables that might affect these calculations would be prohibitive. It has been found that normalizing the metabolic energy costs of work by the individual's body surface area produces a value that varies less among individuals for a given task. Typically, the regression formula of DuBois and DuBois (1916) is used to estimate the body surface area, however a revised formula (Tikuisis, Meunier, & Jubenville, 2001) based on an extensive survey of CF personnel provides more accurate estimates (rms error 0f 0.0241 m^2 or 1.26%)

[5] For example, see: http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html

$$
\begin{aligned}
BSA &= 0.00808 m^{0.44} h^{0.60} \quad \text{(men)} \\
&= 0.01171 m^{0.47} h^{0.55} \quad \text{(women)}
\end{aligned} \tag{4}
$$

where BSA is the body surface area in square meters, m is the body mass in kilograms and h is the body height in meters.

Passmore and Durnin (1955) and McArdle et al. (1981) present extensive lists of metabolic rates for industrial and domestic activities that can be used to estimate metabolic rates of military tasks. Some military tasks, with typical, normative metabolic rates is listed in Table 4. As with other estimates, these values should only be considered approximate; values could vary 25% just due to differences in body size alone.

Table 4. Examples of military tasks and their associated metabolic energy costs in watts (W) A 75 kg man is assumed. (Sources: Anonymous, 1996; Astrand & Rodahl, 1977; McArdle et al., 1981; Wulsin, 1945)

Work Classification	Example	Total Metabolic Rate (W)
Rest	Lying down	80
	Sitting	105
	Standing	175
Light (100-300W)	Office work	110 - 140
	Light bench work	
	Walking	140
	Close order drill with rifle	235
	Machining	275
Moderate (300-400W)	Walking quickly	
	Jogging	
Heavy (400-600W)	Digging foxhole	400 – 600
	Fast jogging	500 – 600
	Obstacle course with light pack and rifle	440
	Machine fitting	450
	Marching, 13kg pack & rifle	475
	Crawling, full equipment and rifle	470
	Field rushes, pack and rifle (5s run/10s lying)	480
Very Heavy (>600W)	Running	600 – 1200
	Digging trenches	750

Sawka and Pandolf (2001) summarize numerous data sources and conclude that the risk of heat exhaustion is negligible at core temperatures below 38°C for compensable heat stress and low to moderate for uncompensable heat stress[6] as shown in Figure 1. While a more liberal criterion of 39°C might seem more appropriate from the figure, commanders in the field would be hard pressed to determine whether conditions would lead to compensable or uncompensable heat stress, yet the difference between the two conditions is considerable. It is apparent that further guidance for field use is required both to ensure the safety of working personnel as well as to ensure that working conditions are optimal.

[6] For compensable heat stress, the required evaporation rate for an exposed subject to maintain homeostasis is less than the maximum dictated by environmental conditions. For uncompensable heat stress, the subject cannot evaporate sufficient amounts of sweat to offset metabolic heat production and heat transfer from the environment.

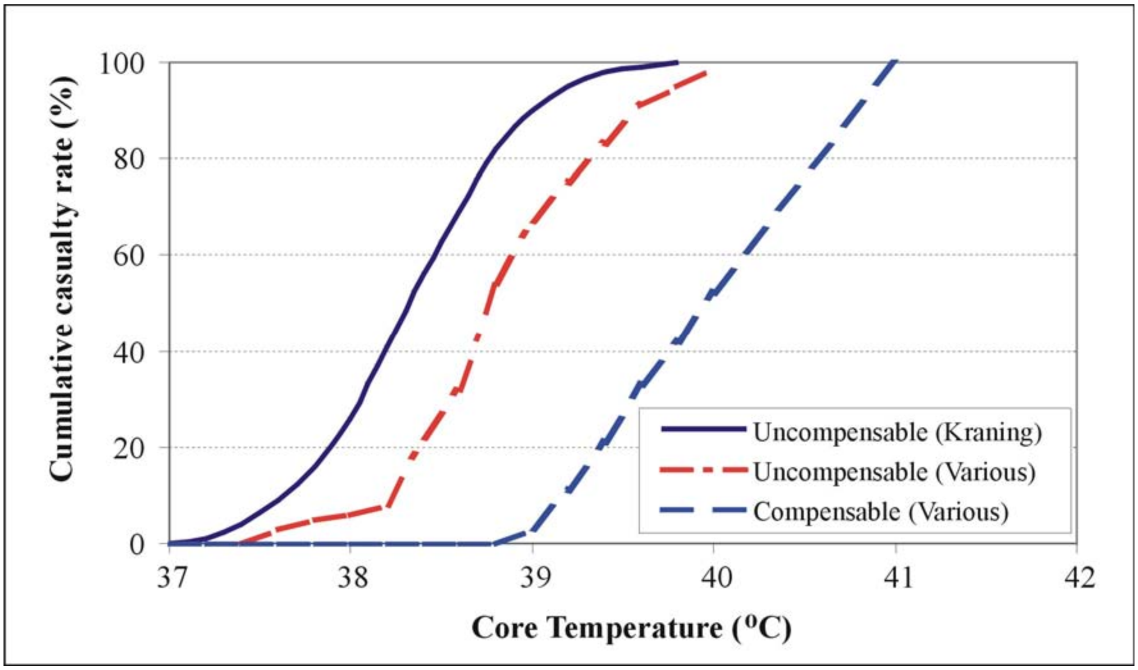

Figure 1. Cumulative casualty rate from heat exhaustion as a function of core temperature during continuous exercise in hot environment. Uncompensable indicates the maximum evaporation rate is less than the required evaporation rate to maintain homeostasis. Shown values are estimated from results presented in Sawka and Pandolf (2001) and should not be considered as accurate as the source.

The two curves for uncompensable heat stress shown in Figure 1 are likely due to differences in experimental conditions, such as work rate, clothing properties, and environmental factors that affect heat loss such as high temperature, high humidity or high solar load; other factors such as individual differences or uncontrolled physiological states could also bias the results. The steep rate of increase in casualty rate under these conditions makes it difficult to predict casualty rates from heat exhaustion in the field. In order to be practicable, a computational aid would be required that relates specific contextual information (such as work rate, environmental conditions, etc.) with human sciences data and further research on core temperature response to work and rest cycles.

In a comfortable environment, heat loss from the body is approximately equal to the metabolic heat production. As the metabolic heat production increases, the ability to dissipate excess energy decreases and body temperature rises. In hot environments, where the dry bulb temperature exceeds the skin temperature, the excess energy can typically only be dissipated through the evaporation of sweat, although in principal radiant heat transfer to a cold surface could also dissipate some of the excess energy. When solar loads or thermal radiation from hot surrounds also contribute to the heat storage by the body, sweating becomes the only method to maintain a healthy body temperature. Replenishment of the lost sweat by drinking water is a commonly quoted critical aspect of working safely in hot environments.

Method

The approach taken in this study was a combination of in-house and contracted activities. While the main emphasis of this report is on the analysis of thermal strain, additional information is included that was part of the project and relevant to working in hot environments.

A literature review of heat strain and heat strain effects was conducted both under contract as well as in-house. The purpose of this study was to assess the current state of knowledge of the effects of thermal strain on performance, both physical and cognitive. Additionally, the review was to identify those factors that contribute to, or at least correlate with, performance degradation and note any models of performance degradation based on these factors.

A task analysis of the CF CC130 Hercules aircraft Maintenance Technician's job was conducted under contract to assess the physical and mental demands placed on the technicians, identifying possible sources of error that could arise due to working in hot environments.

The analysis of thermal strain resulting from work and rest in hot environments was conducted using the Integrated Performance Modelling Environment (IPME) with a thermoregulatory model. Computational models of continuous work and work-rest cycles were developed in IPME at DRDC Toronto to control the thermoregulatory model. The task network model represented a generic activity while the thermoregulatory model predicted the physiological response over time. Simulations using these models were conducted, to predict heat strain responses to heat stress under various conditions.

Apparatus

The human performance modelling and simulation software IPME (Integrated Performance Modelling Environment[7]) version 3 was used to develop simple models of the environment, the characteristics of the technician's clothing and generic activity levels. The model focussed on representing the physical activity that would have an impact on the health and safety of the technician rather than the effect of heat strain on either physical or cognitive task performance, to better compare the results with published guidelines for working in hot environments.

The IPME network representing intervals of work and rest is shown in Figure 2 below. This application of IPME is very simple and constitutes a small range of its potential use. Should additional information of heat strain on mental and physical task become available, more complex models representing the Aircraft Technician's actual duties could be developed to predict performance. Such models, when coupled with criteria such as acceptable error rates, could be used to further refine work-rest cycle durations, or to develop procedural methods of further reducing the risk of error during atypical working conditions such as work in extremely hot environments.

[7] Micro Analysis and Design Inc, Boulder, CO.

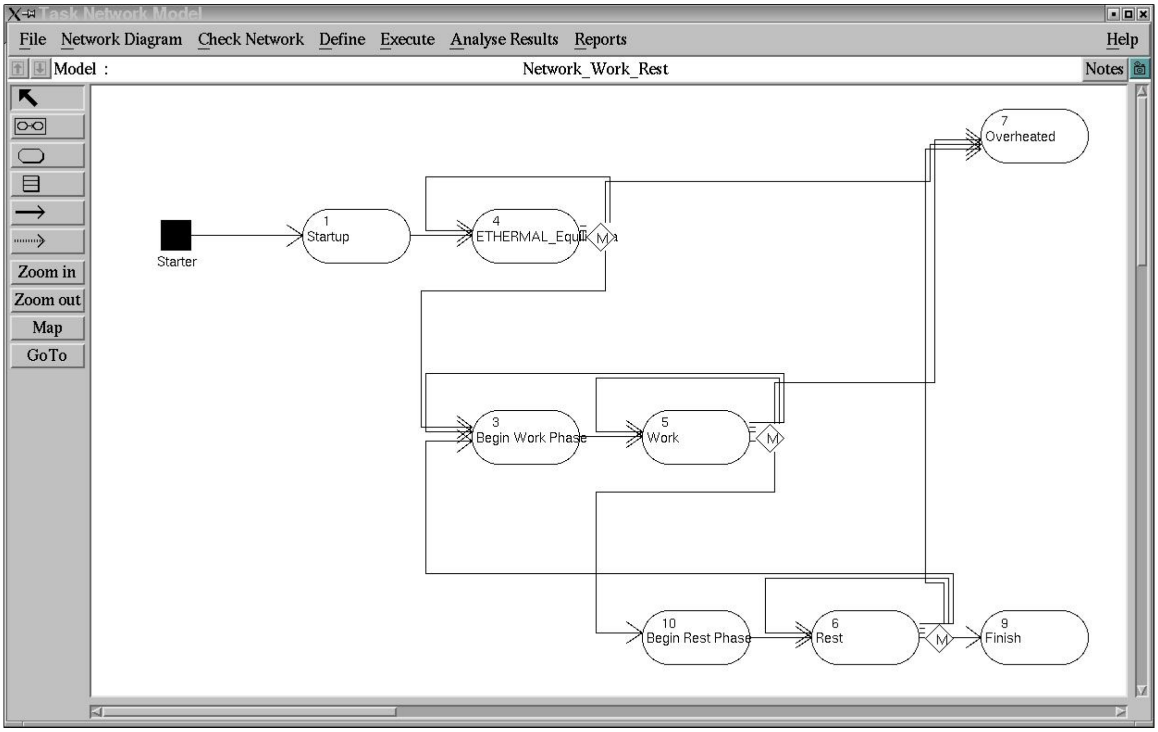

Figure 2. IPME network representing periods of work and rest. The network for continuous work was similar, omitting tasks 6 and 10.

Thirteen subroutines were developed for the IPME environment model to calculate meteorological variables and WBGT values for experimental conditions. These subroutines were based on the literature for thermodynamic properties, meteorological relationships, and empirical functions for estimating heat transfer.

These IPME task models controlled a proprietary, non-commercial thermal physiology model developed by QinetiQ[8] Ltd. This thermoregulatory model is a multisegment, two dimensional representation of the physiological and physical process of human thermoregulation in both hot and cold environments, including air or water exposure. The model predicts blood and heat flow between and within the various segments, sweating, heat and moisture loss to the environment, and the resulting temperature of the various body segments. QinetiQ has conducted limited validation of this model using available data from other in-house studies.

The QinetiQ thermal model takes the following inputs (among others) during the course of a simulation: environmental conditions (dry bulb temperature, relative humidity, solar radiation, wind speed), task demands (net exercise metabolic rate), and operator characteristics (weight, percent body fat, clothing thermal insulation and water vapour permeability for each segment, body orientation to solar radiation, water consumed). The model returns (among other variables): the core and skin body temperatures, the water loss rate and hydration level, and the heat loss rate. The model distribution package also provides performance shaping functions (PSF) that predict changes to task duration and probability of failure as functions of the operator thermal and hydration state, as well as perceived comfort, although these PSFs were not used in this study.

[8] QinetiQ Ltd, formerly part of the UK Defence Research Evaluation and Research Agency.

IPME and the QinetiQ thermal physiology models were run on Intel based, P3 personal computers running Red Hat Linux 7.2. The thermal model requires a simulated 30 minute equilibration period at the beginning of each run to establish a stable temperature distribution. During this simulated 30 minutes, the environmental conditions are kept at 25ºC, 50% relative humidity with the subject at rest. Communications between IPME and the thermal client and data collection occurred every 5 minutes of the simulated 10 hour work day and the 30 minute equilibration period, taking approximately 4 minutes of real time to complete each simulation. The raw data were reduced offline using custom software developed in-house and spreadsheet packages.

Evaluation and settings

The IPME Measurement Suite was used to set up a number of experimental conditions. The following independent factors were manipulated

- Dry Bulb Temperature (25 - 50°C)
- Relative Humidity (10-70%)
- Solar Radiation (0-500 W/m^2)
- Wind Speed (0.5 – 10 m/s)
- Exercise (0 – 1000 W, total metabolic rate less the resting metabolic rate)
- Work Duration (10 – 70 minutes)
- Work-Rest Ratio (0.05 – 1.65, ratio of time worked to time rested)

Not all levels of each factor were assessed in combination. The number of conditions to be assessed was prohibitive for reasonable step sizes within the range for each of the above factors. The environmental conditions were selected to give WBGT values that were similar to published tables to assist comparison with recommended work and rest durations. Metabolic work rates were similarly selected.

The subject in all simulations was assumed to be a man, weighing 75 kg, with 11% body fat. The clothing was assumed to be representative of standard combat clothing with intrinsic thermal resistance of approximately 0.1 m^2 K/W (0.7 CLO) and water vapour permeability $4x10^4$ m^2 Pa s/g (equivalent to 7.5 mm of still air or approximately 2.6 vapour void fraction used by the QinetiQ model). The clothing properties varied slightly over the body segments as the head, forearms and hands were assumed uncovered, combat boots were worn on the feet, a t-shirt was worn on the torso under the combat shirt; more detail is shown in Figure 3. A radiative viewfactor, or radiative load fraction, of 0.3 was used in the modelling. This represents the fraction of the total surface area that is effectively exposed to thermal radiation, in this case, solar radiation. The QinetiQ thermal model effectively adds additional resistance by computing the effects of the external boundary layer between the outermost layer and the environment.

The rest phase of the simulation was usually assumed to occur under the same environmental conditions as the work phase. In a few studies, a less stressful resting environment was imposed with a dry bulb temperature of 25°C, a relative humidity of 10%, a wind speed of 0.5 m/s, and no solar load. To minimize any effect of dehydration in the simulation, the operator was given the same

amount of water that was lost due to sweating and respiration every 5 minutes. The water was specified to be at the instantaneous core temperature to prevent disturbing the energy balance.[9]

The criteria used to select reported values of acceptable work and rest intervals in the order of application were

1) the core temperature must remain below 38°C throughout the simulation

2) the combination of work and rest durations that maximized the average amount of work done in a work and rest cycle

3) the longest work duration of maximal average work and rest cycle

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[9] Regular drinking of cool water to offset sweating is an energy sink that is comparable to the amount of energy lost due to respiration over the same period and thus another means of directly reducing heat strain.

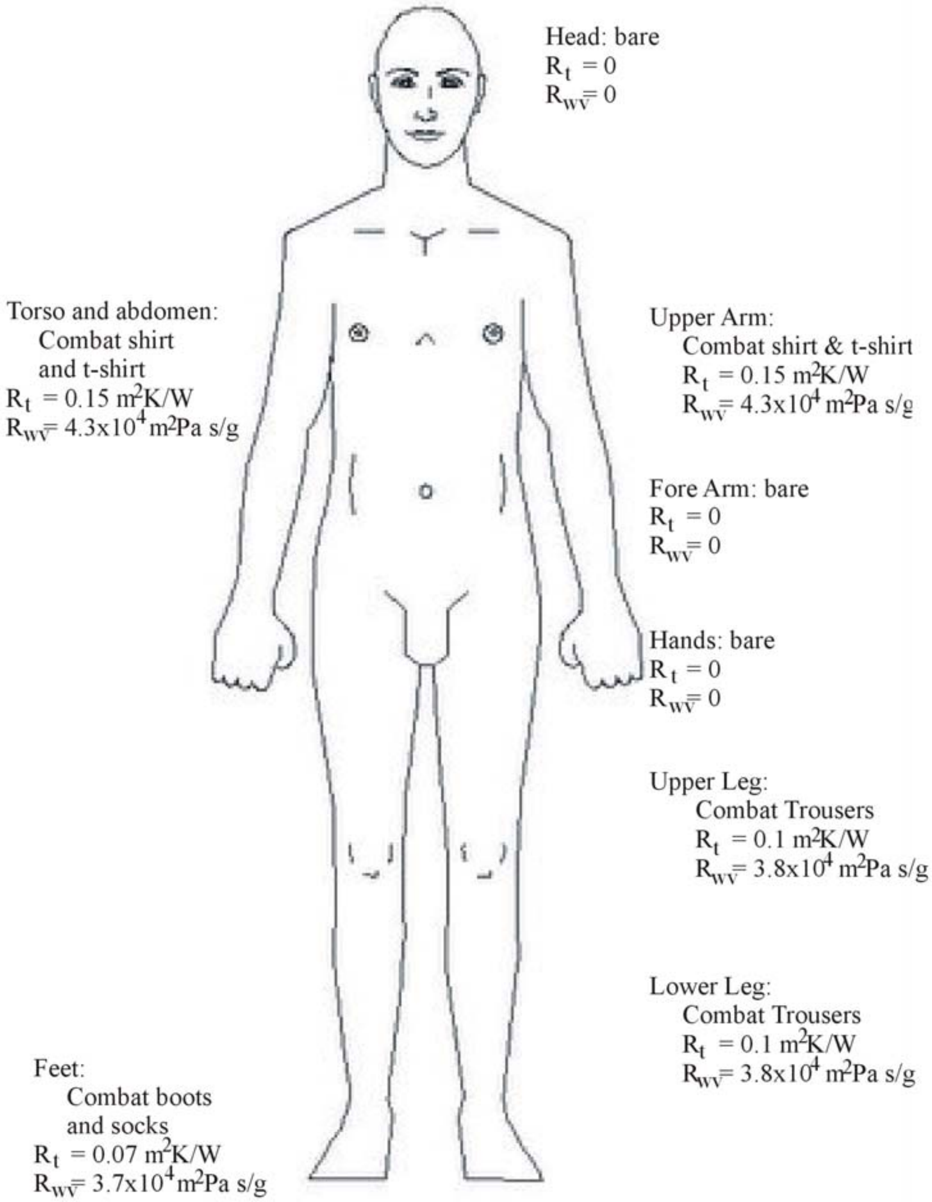

Figure 3. Intrinsic thermal and water vapour resistance values assigned for the clothing assumed in the study. A thermal resistance of 0.15 m^2 K/W is approximately equivalent to 1 Clo; 4.3x10 m^2 Pa s/g of water vapour resistance is approximately equivalent to 8 mm of still air, or a vapour void fraction of about 2.25.

The Measurement Suite data collection and the snapshot utilities of IPME were used to collect results every 5 minutes within the simulation. The following dependent measures were recorded

- Rectal Temperature (°C, as representative of the core temperature)
- Skin Temperature (°C, mean over the whole body)
- Total Metabolic Rate (W)
- Water loss (L, cumulative loss due to sweating and respiration)
- Wet Bulb Temperature (°C)
- Natural Wet Bulb Temperature (°C)
- Globe Temperature (°C)
- WBGT Index (C)

The work day duration was set to be 10 hours. It was assumed that if the criteria used to assess performance during this work day were not exceeded then it would be unlikely that they would be exceeded in practice even if somewhat longer work days were experienced. The simulation model included an extra 30 minutes at the beginning of each simulation under common, benign conditions to allow the QinetiQ thermal model to stabilize.

The criterion of a maximum core temperature of 38°C for exposure limits was used in this study, as set out by the ACGIH. This is a conservative criterion intended to reduce the risk of heat strain casualties to an acceptable level under most conditions. If this value was exceeded at any point in a simulation, that combination of work-rest ratio and work interval duration was deemed to have failed for that set of environmental and exercise conditions. For those sets of conditions that passed this criterion, the set of work interval duration and work-rest ratio that produced the longest work interval was selected.

Results were also obtained for continuous work conditions under similar sets of environmental conditions. These results were further assessed to predict the time to reach a number of core temperatures (38, 38.5, 39 and 39.5°C) or an equilibrium state. The current model does not include estimates of physical fatigue and merely indicates the duration that work may be sustained without incurring an undesirable level of heat strain.

The QinetiQ model includes dehydration effects in the physiological responses. To minimize these effects, the operator was modelled as drinking as much water as was lost due to sweating in each 5 minute interval, limiting the water deficit to respiratory losses. The total water loss rate was assessed during post processing as the cumulative sum of the respiratory and sweating water losses divided by the simulation duration.

When the QinetiQ model core temperature exceeds 39.5°C, the internal integration time step required for stability becomes very small, increasing the computation time prohibitively. Each simulation for a given set of conditions was automatically terminated when the core temperature exceeded 39.5°C to prevent excessive computation time.

Constraints on current results

There are a number of failings with the current study that make the results obtained unsuitable as general guidelines governing work and rest in hot environments. Some of these concerns are

- results were not validated with empirical data from controlled human experiments under similar conditions

- thermal model only validated by QinetiQ and has not received independent validation
- limited time did not permit an exhaustive or even adequate assessment of any of the significant variables that affect predicting work schedules
- the rate of core temperature change is important to task performance, but the critical value appears to depend on the characteristics of the task (Hancock & Vasmatzidis, 2003)

Principal among these points is that the results have not been validated with human trials. Until this step has been completed, there is little confidence that the findings of this study are safe for conditions that lie outside of those already reported in the literature. Using the rate of core temperature change directly may make selecting a work-rest schedule difficult although perhaps an average rate of core temperature change with limits on exposure duration may make such an approach feasible.

Results and discussion

Because of the concerns raised in the previous sections, the following results should not be considered authoritative. The lack of validation against empirical studies coupled with only considering a few of the relevant factors affecting heat strain leave inadequate confidence in these results for general use. Personnel must use the results of this study with caution, preferably with extensive experience working in hot environments and with the understanding that injury or death due to overheating may occur. Further, this report only considers limits on physical work associated with thermal strain; they do not address work limits associated with fatigue or muscular strength.

Summary of heat strain literature review

The literature review of the cognitive effects of working in hot environments was published as a DRDC Toronto contract report (Bruyn & Lamoureux, 2004). Most of the literature reviewed focused on defining exposure limits, attempting to make direct links between performance and the environmental conditions; fewer studied the intermediate effects of the working conditions on operator state and the subsequent link to performance changes. While the former is a sensible approach for publishing guidelines to the public, a more fruitful research approach supporting such guidelines would likely be to study the effect of thermal stress on thermal strain, then linking the resultant operator state to safety and performance guidelines.

Most of the studies were concerned with establishing exposure limits that ensure the physiological well being of the workers rather than assessing the effects on cognitive or physical performance. While some studies did report cognitive and physical task performance during work in hot environments, not all were in agreement about the effects, even on similar tasks. As an example, in two consecutive studies with similar tasks, Cian and colleagues found significant effects, then subsequently no effect of hydration on performance (Cian, Barraud, Melin, & Raphel, 2001; Cian et al., 2000). It would appear that effects of thermal strain on performance depend upon the task under study, the experimental approach and, in some cases, confounding factors.

Of the operator state variables, core temperature has received the most attention as the prime factor affecting performance. Other factors, such as the rate of change of core temperature and hydration level are also thought by some researchers to be key elements in performance degradation.

Hancock (2003) and colleagues have documented task performance degradation as a function of the rate of change of core temperature. While the published results are not yet at the stage of formal models, Hancock has described broad effects on particular classes of tasks each with a threshold criterion for the rate of change of core temperature that produces significant performance degradation. Hancock (2003) notes that task complexity is a key factor of the effect of thermal strain on performance. Simple tasks such as reaction time and mental transformation tasks are less affected by thermal strain than more complex tasks such as vigilance, tracking and multitasking. Also, tasks that are well learned and have been reduced to a skill are less likely to be affected than tasks requiring concerted attention. From studies of multitasking, Vasmatzidis, Schlegel, & Hancock (2002) suggest that tasks that principally involve working memory are least susceptible to thermal strain while tasks that are largely manual output or perceptually demanding will be most affected by thermal strain. Hancock (2003) notes that incentives and expectation can compensate for the effects of thermal strain but that the effect is likely transient and may not come into play during routine work. The effect on vigilance is of particular relevance to aircraft technicians since inspection and alertness for problems is a major part of their role in maintaining flight safety.

There are other studies of hydration effects on performance that seem to support both significant and nonsignificant effects. Bradley & Higenbottam (2000), Gopinathan et al. (1988), Sharma et al. (1986) all found significant evidence of performance degradation on cognitive tasks due to dehydration while Tikuisis and colleagues (Tikuisis, 2005; 2002; Tikuisis, Shin, Keefe, & Taylor, 2005) found none. Hancock notes, however, that there are a number of confounding variables at play in studies such as these and effects may be masked by other uncontrolled variables.

None of the reports reviewed for the current proposed formal models of performance decrements. Hancock & Vasmatzidis (2003) come the closest to providing sufficient information in the open literature surveyed, although they do not link performance to thermal strain but to exposure, making generalization impossible without access to their data. A meta analysis of the literature[10] indicates a clear, significant effect of dehydration on performance degradation, and this is reflected in the QinetiQ performance shaping factor models distributed with the thermal strain model[11]. The report was unavailable for the current review, but it included models of several performance shaping factors based on empirical data from several sources.

In summary, the literature remains uncertain on the precise effects of thermal strain on performance but there is mounting evidence that several mechanisms are relevant and must be controlled in studies to attribute effects appropriately. Few formal performance models exist but there appears to be sufficient data from a number of research institutions that could be used to develop validated models.

Summary of CC130 Aircraft Technician task analysis

A mission/function/task analysis of the CC130 Aircraft Technician's job has been published as a DRDC Toronto contract report (Hunter & Armstrong, 2004). The analysis covered a range of activities including routine maintenance and inspection (generally light duty tasks) as well as conditional maintenance and repairs (may be heavy duty tasks), documenting the mental and physical demands associated with the tasks.

Several maintenance crews may be deployed on a mission comprising a fleet of several aircraft. This allows around the clock service made up of 6 to 8 hour shifts per crew with additional time devoted to paperwork. When deploying to hot climate zones, crews use portable air conditioning units when required, particularly when working in confined areas that are not air conditioned; heavy work and work on the exterior of the aircraft that must be done outside of a hangar is often scheduled during the night to alleviate thermal stress.

Commanders are instructed in the hazards and remedies for heat stress, and must remain vigilant to adverse affects of heat strain since self monitoring may not be adequate protection in an operational environment. Crews are encouraged to take frequent and adequate breaks, but teamwork and backup become increasingly important to avoid errors that will arise because of thermal strain.

The CF Aircraft Technician trade maintains a culture of safety through attention to detail, accuracy rather than speed of work, training and certification, cross checks and independent review of work done. This culture does not seem to be adversely affected by operational demands and if this work environment can be maintained in the field, then thermal stress may not be a significant issue.

[10] Wilson, A., Bunting, A. The prediction of the effects of a hot environment on cognitive performance. DRA/CHS/A&N/CR/96/007. March 1996

[11] Belyavin, A.J., QinetiQ Ltd. Personal communications, 2004.

The task analysis indicates that while some of the tasks faced by Aircraft Technicians involve heavy physical labour (such as engine replacement), the majority of the tasks have low physical demands. These light tasks typically involve inspection and evaluation or judgement, looking for evidence of malfunction. The characteristics of these inspection tasks, routine in nature and related to vigilance, likely with infrequent problems, are prime candidates to be adversely affected by thermal strain. This suggests that error rates may increase during work in hot weather and that consideration of errors be part of an expanded study of work in hot environments to assess whether current operating procedures maintain acceptable levels of risk.

Continuous work

The results from approximately 400 simulations analysing thermal strain during continuous work are summarized in 0. This represents about 30 hours of continuous computer computations that would have required considerably more time if human trials were considered for each condition. These results represent a starting point to determine an average metabolic rate that could be used to determine appropriate rest and work durations. 0 also shows expected times to reach a number of different core temperatures and predicted water consumption rates required to offset sweating and respiratory water losses.

The limiting metabolic rate for continuous work was estimated from the data in 0 and is shown in Figure 4 as a function of the WBGT(C) index. Work rates and resulting core temperatures were interpolated to obtain a metabolic rate that would produce an equilibrium core temperature of 38°C at each set of environmental conditions. The graph indicates that the limiting metabolic rate for continuous work is not an exact function of WBGT, as previously noted, although the WBGT appears to be a moderately good indicator of thermal stress. For reference, resting metabolic rate is approximately 100 W, while 500 W is often assumed to be a maximum voluntary work rate.

At certain ambient conditions, the limiting work rate in Figure 4 at high WBGT values can exceed that for similar or lower WBGT values, although there is a general trend of decreasing work rate with increasing WBGT. This reflects the differences and importance of the various methods of heat loss from the body as well as the formulation of the WBGT index. Since the WBGT is an index rather than a temperature, combinations of more fundamental meteorological factors can result in similar WBGT values, but have different heat and moisture transfer values. This results in slightly different levels of heat stress due to differences in the amount of energy dissipated and can lead to equilibrium core temperatures that differ by a few tenths of a degree Celsius despite similar WBGT values. For example, for high WBGT values (greater than ~34C), some environmental factor combinations result in unsafe working conditions (indicated by limiting metabolic rate values of 0W in Figure 4), while light work may be safely performed at other, similar or even greater WBGT values. For instance, in one case with a WBGT of 33.8C (arising from a dry bulb temperature of 35°C, a relative humidity of 70%, no wind, solar radiation of 200 W/m^2), core temperature continually increased even at rest, while in another case with a WBGT of 34.0C (arising from a dry bulb temperature of 40°C, 50% relative humidity, no wind, and no solar load), light work at a total metabolic rate of about 200 W was predicted to be acceptable.

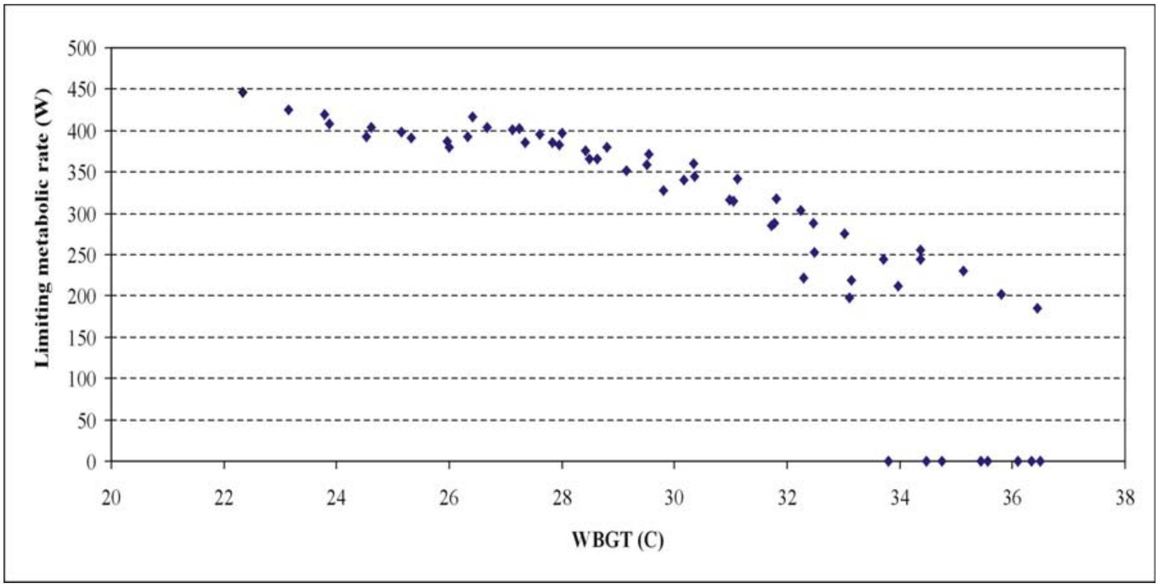

Figure 4. Estimates of the limiting metabolic rate for continuous work as a function of WBGT(C) based on a maximum safe core temperature of 38°C. Limiting values of metabolic rate equal to 0 (around WBGT 34 to 37) indicate that the particular combination of environmental conditions exceeded safe conditions even at rest.

0 includes predictions of equilibrium core temperatures and the time to reach selected core temperatures. This type of data could be used to provide commanders with a risk assessment of incurring thermal strain casualties to consider with other risks associated with decisions and expected scenarios during a mission. Each of the elevated core temperature values carries an associated risk of heat illness as shown in Figure 1. The times in 0 do not, in their present state, provide an adequate representation of what the maximum core temperature response would be during work and rest intervals even if the average metabolic rate is similar; this will be discussed in greater detail later in this section.

Table 5 contains ratios of rest duration to work duration (t_{rest}/t_{work}) for various working metabolic rates at a number of WBGT values calculated according to Equation 1. Values have been aggregated into bins approximately centred on the quoted WBGT value and the largest rest/work ratio in each bin selected.

At low work rates, continuous work is predicted to be safe up to WBGT(C) values that substantially exceed current guidelines. Generally, as the WBGT index increases the amount of rest required increases relative to the amount of work done. As the work intensity increases, the amount of rest required to allow adequate heat transfer also increases. At the higher WBGT values, where the ability to dissipate energy is most compromised, metabolic heat production substantially exceeds heat loss, necessitating longer rest periods to recover.

Table 5. Estimate of the ratio of rest duration to work duration at various WBGT values for average metabolic rates based on the formula in Equation 1 proposed by (Brake & Bates, 2002). These values should not be used to determine work and rest durations as core temperatures would exceed the recommended safe limit of 38°C during work.

WBGT (C)	Rest/Work Ratios					
	Total Working Metabolic Rate					
	225 W	300 W	500 W	700 W	900 W	1100 W
22	Continuous	Work	0.2	0.7	1.3	1.9
23	Possible		0.2	0.9	1.5	2.1
24			0.3	1.0	1.6	2.3
25			0.4	1.0	1.7	2.4
26			0.4	1.0	1.7	2.4
27			0.4	1.0	1.7	2.4
28			0.4	1.2	1.9	2.6
29			0.6	1.3	2.1	2.9
30			0.6	1.4	2.2	3.0
31			0.9	1.8	2.8	3.7
32		0.2	1.3	2.5	3.7	4.8
33	0.1	0.6	2.1	3.7	5.3	6.8
34		0.5	2.0	3.5	4.9	6.4
35	0.1	0.7	2.5	4.2	6.0	7.7
36	0.5	1.4	3.7	6.1	8.4	10.8

The predicted rest/work duration ratio based on the above analysis is compared with corresponding values derived from American and Canadian military guidelines in Table 6. The rest/work ratios from each source have both similarities and differences to the other two sets, with all sets being most similar at the lowest WBGT value. At the highest WBGT value, the rest/work ratios predicted from Equation 1 and the continuous work analyses in this study are substantially less than that of both the US and CF publications. Although it is difficult to say with certainty why the differences occur, it is likely that the continuous work results of this study and Equation 1 are too liberal because they do not consider the transient nature resulting from work and rest intervals as discussed in the next section.

Table 6. Comparison of approximate ratio of rest time to work time estimated from Table 2 and Table 3 with values from this study that are based on continuous work analyses and Equation 1. The solid cells indicate continuous work is feasible; "-" means no recommendation was given in the guideline; NR means Not Recommended by the guideline.

WBGT	Metabolic Rate	Rest/Work Ratio		
		US	CF	This study
C	W			
25	250	Continuous	Work	Possible
	350			
	500	0.5		0.4
	700	-		1.0
29	250			
	350	0.5		
	500	1.0	0.7	0.6
	700	-	2.0	1.3
31	250	0.2	0.3	
	350	2.0	0.3	
	500	5.0	3.0	0.9
	700	-	NR	1.8

Based on these results, simulation of thermal strain during continuous work, even when used with Equation 1, seems to be inappropriate for determining work and rest interval durations. Nevertheless, this approach can be used to establish an estimate of the minimum rest to work duration ratio, since a smaller ratio would result in overheating. This information is a valuable starting point that narrows the analysis scope, eliminating inappropriate ratios from consideration and thereby saving computation time. It is possible that, with modification, estimates from Equation 1 and continuous work analyses could be improved to the point where they could be used safely. This would require corrections based on work rates and durations from work-rest analyses or empirical studies as well as corrections for other factors relevant to thermal strain (Table 1) but not considered by the equation's simple relationship.

Alternating work and rest

The reason for alternating work and rest intervals during work in hot environments is to safely allow work at metabolic rates that exceed the limiting metabolic rate of continuous work. This is accomplished by providing a recovery period that allows the core temperature to fall towards normal, providing capacity for additional work without unsafe core temperature excursions. The result is an oscillating core temperature that increases during work with a profile similar to that of continuous work at the higher work rate, followed by a cooling off period during rest as shown in Figure 5.

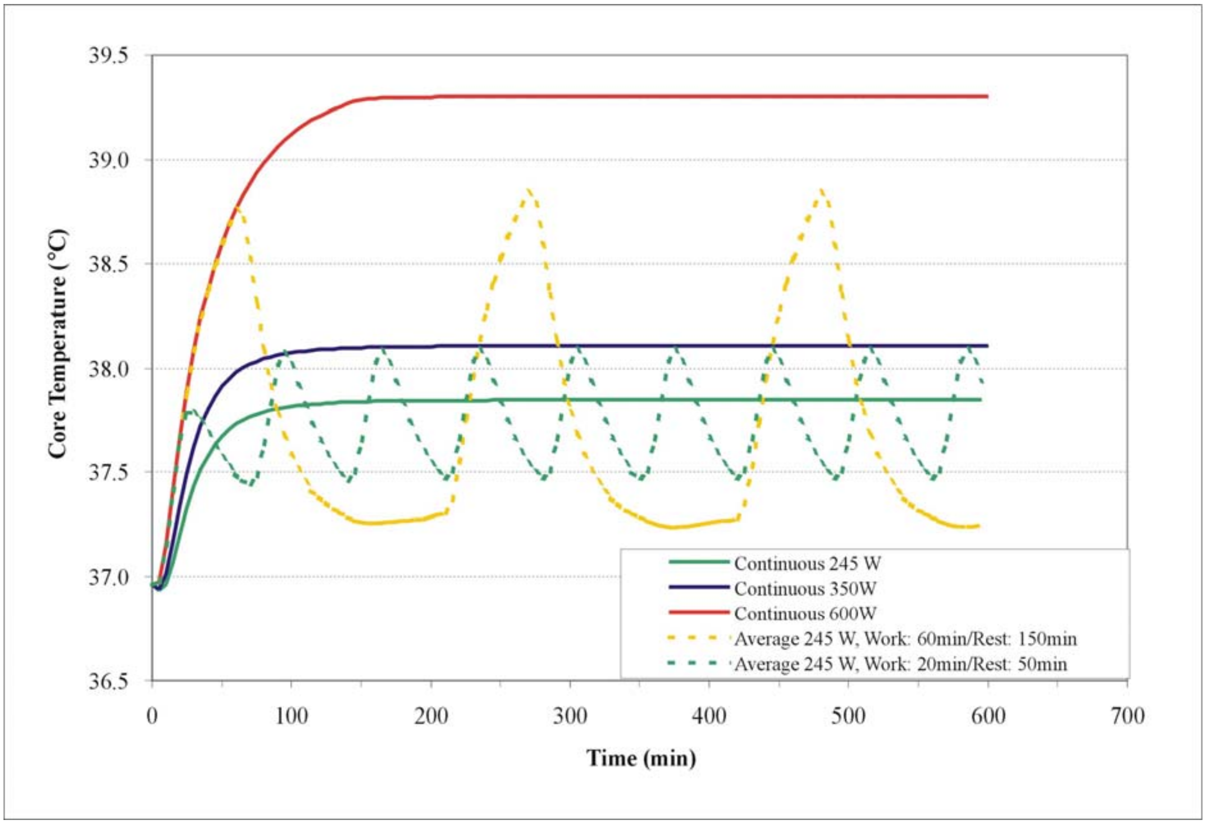

*Figure 5. Comparison of predicted core temperature response continuous versus intermittent work rates for WBGT=30C (Dry Bulb Temperature=45°C, Relative Humidity=5%, Wind Speed=0.5 m/s, Solar Radiation=300 W/m²**.)***

In Figure 5, the lowest solid green line represents the core temperature response during continuous work at about 245W. Under the condition in the caption, this would be a safe work rate while the middle solid blue line, at a total metabolic rate of about 350W, would cause the core temperature to just exceed the safe 38°C criterion after approximately 65 minutes. The upper solid red line, at a total metabolic rate of 600W, would result in an equilibrium core temperature of about 39.3°C, well above the recommended safe limit, crossing the 38°C threshold at approximately 30 minutes.

The two sets of results represented by the dashed lines show the predicted core temperature responses during alternating work and rest intervals (under the same environmental conditions as the continuous work simulations.) Both of these intermittent work trials have a time weighted average metabolic rate equivalent to the lowest continuous work rate (245W), and each has the same ratio of rest to work duration (t_{rest}/t_{work}=2.5)[12].

The upper dashed, yellow curve in Figure 5 has work intervals of 600 W lasting 60 minutes, each followed by a rest interval of 150 minutes. The core temperature rises sharply during work to reach a maximum of approximately 38.8°C, substantially above the recommended level of 38°C. From Figure 1, subjects with core temperatures at this level have a 60-80% risk of becoming a heat strain casualty for uncompensable or a small risk (<10%) if compensable heat strain[13]. During rest, the core

[12] Note that, from Equation 1, $T_{W\%} = 100\ t_{work} / (t_{rest}+t_{work})$

[13] Uncompensable heat strain occurs when the maximum possible evaporative cooling resulting from sweating is insufficient to balance metabolic heat production and dry heat transfer from the body.

temperature reaches a lower equilibrium value and the rest interval is about 50 minutes longer than required to keep the core temperature below the safe limit.

The lower dashed, green curve has work intervals of 20 minutes and rest intervals of 50 minutes. While the predicted maximum core temperature still exceeds the recommended 38°C, the excursion is small, and comparable to that of the intermediate continuous work rate of 350W; the risk of heat strain casualties in this case would be low (10-20% for uncompensable or negligible for compensable heat stress.) During rest, the core temperature does not recover as much as in the other intermittent work case but neither does the operator spend time resting without any additional recovery of core temperature.

The core temperature response during the two intermittent work conditions can be seen to be quite different because of the duration of each work and rest interval. In both of the intermittent work sessions, the core temperature increases while working then decreases during rest, but the extent to which the core temperature increases is dependent on the duration of the work interval. This demonstrates why a guideline for work and rest intervals based on continuous work alone is inadequate. Figure 5 also indicates that both the work and rest durations, or equivalently the work duration and the rest/work ratio, are important to the analysis of safe work in hot environments; further, these two variables need to be optimized as interacting factors when determining guidelines and cannot be considered independently.

Table 7 and Table 8 are a compilation of results obtained from approximately 4500 simulations of thermal strain during intermittent work conducted at DRDC Toronto and under contract (Armstrong, 2005); it would not have been practicable to run this many human trials in a laboratory. These simulations took approximately 300 hours of continuous computation time in addition to set up and analysis time. While much of the data reduction was automated through custom software, collating and interpretation of results was performed manually in Microsoft Excel™.

Table 7 represents suggested work and rest durations when rest occurs under the same environmental conditions as work; Table 8 represents work and rest intervals when the resting environmental temperature is reduced to 25°C. These studies examined a number of discrete conditions to determine appropriate durations of work and rest.

The reported work and rest interval durations may not be optimal as the analysis was not exhaustive over the levels considered, but the tabulated work and rest duration results should meet industrial health and safety standards for maximum core temperature, subject to the accuracy of the thermal model.

In many cases, more than one set of work and rest conditions satisfied the safe working criteria and allowed longer work intervals than those reported in these tables, but the average amount of work done in each cycle was lower. Table 9 shows three sets of work and rest duration combinations that maintained a safe core temperature. As the work duration increases, the time that must be spent resting increases disproportionally since the heat production during work is greater than the heat loss during rest. The result is that the fraction of time in a work and rest cycle decreases as the work duration increases. This means that recommended work and rest durations will differ depending on the criteria used to assess them. For this report, the fraction of time spent working was selected as being more important than the work duration, but in some scenarios the opposite would be more appropriate. Deciding on an appropriate work and rest cycle is thus both task and context dependent, requiring an assessment of what is most appropriate for a particular situation.

Table 7. Work and rest durations (in minutes) and Rest/Work ratio (R/W) for various metabolic rates and WBGT (C) values from a limited set of discrete trial combinations of work and rest durations. The criteria used to select the values in this table were: first, core temperature must not exceed 38°C at any point in the trial; second, the set of work and rest durations that maximized the average work done; third, the longest work duration. Ambient conditions were the same for both rest and work. The green shaded cells for 225 and 300 W indicate that continuous work is possible while the red shaded cells in the 900 and 1100 W cells indicate that work is not recommended at those rates for the environmental conditions studied.

	Total Metabolic Rate (W)																	
WBGT	225 W			300 W			500 W			700 W			900 W			1100 W		
(C)	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W
23	480	96	0.2	480	96	0.2	30	24	0.8	10	15	1.5	10	22	2.2	10	200	20
26	480	96	0.2	480	96	0.2	20	16	0.8	10	15	1.5	10	40	4.0	10	200	20
30	480	96	0.2	480	96	0.2	10	8	0.8	10	15	1.5	10	200	20.0			
33	480	96	0.2	480	96	0.2	10	12	1.2	10	40	4.0	Work	Not	Recom	mended		

Table 8. Work and rest durations (in minutes) and Rest/Work ratio (R/W) for various metabolic rates and WBGT(C) values. The environmental conditions at rest differed form working conditions only in the dry bulb temperature which was 25°C. Selection criteria are the same as in Table 7. The green shaded cells (225 and 300 W) indicate that continuous work is possible

	Total Metabolic Rate (W)																	
WBGT	225 W			300 W			500 W			700 W			900 W			1100 W		
(C)	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W	Work	Rest	R/W
23	300	75	0.3	300	75	0.3	40	62	1.5	20	31	1.5	10	15	1.5	10	40.0	4
26	300	75	0.3	300	75	0.3	30	46	1.5	10	15	1.5	10	15	1.5	10	40.0	4
30	300	75	0.3	300	75	0.3	30	46	1.5	10	15	1.5	10	22	2.2	10	40.0	4
33	300	75	0.3	300	75	0.3	20	31	1.5	10	15	1.5	10	22	2.2	10	200.0	20

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Table 9. Comparison of acceptable work and rest durations at a WBGT(C) = 30 showing the difference longer work durations has on the fraction of time that can be safely spent working at a total metabolic rate of 500 W.

	Acceptable Work and Rest Intervals		
Work (minutes)	10	20	40
Rest (minutes)	8	24	800
Rest/Work Ratio	0.8	1.2	20
Fraction of time spent working	0.56	0.46	0.05

More simulations were run with both work and rest occurring at the same environmental conditions, as this is the more stringent case. Because of this, the values in Table 8 are less refined than those of Table 7 although optimization could be improved for both tables. In these tables, there are several cells that contain the same work and rest durations, or their ratio, despite different WBGT or metabolic rates. This implies that the analysis was not sufficiently complete or sensitive to the factors to discriminate among these conditions, but additional simulations would provide that level of sensitivity if desired.

Despite the restricted number of simulations under cool rest conditions, comparison of Table 7 and Table 8 indicates that providing a cool resting environment can extend work duration somewhat and even allow very heavy work under conditions not recommended in a hot rest environment. The effects are not completely evident from these data since the optimization process was not complete and the rest/work ratios in Table 8 are somewhat misleading. Indications are that work durations can be extended or rest periods reduced, but only slightly from the corresponding hot rest conditions.

A rational hypothesis can be formed to explain this effect and evidence is shown in Figure 6. During the work phase of both the cool and hot rest conditions, the core temperature response is similar, being dominated by the high metabolic heat production (500W in this case). During rest in a cool environment, the core temperature initially decreases at about the same rate as in the hot resting condition, but then continues its asymptotic decrease with time at a faster rate than in the hot rest condition to achieve a lower core temperature (about 0.2°C lower) before resuming work. Somewhat surprisingly, the working metabolic heat production quickly overcomes the core temperature “reserve” and achieves a maximum temperature only slightly lower than the hot rest case (about 0.05°C) lower, and projecting forward, would have only afforded a few more minutes of work before reaching the same maximum temperature (about 45 minutes of work with a cool rest compared to 40 minutes of work with a the hot rest). The average sweat rate in the hot rest condition was almost 50% higher than in the cool rest; about 250 ml/h compared with 180 ml/h.

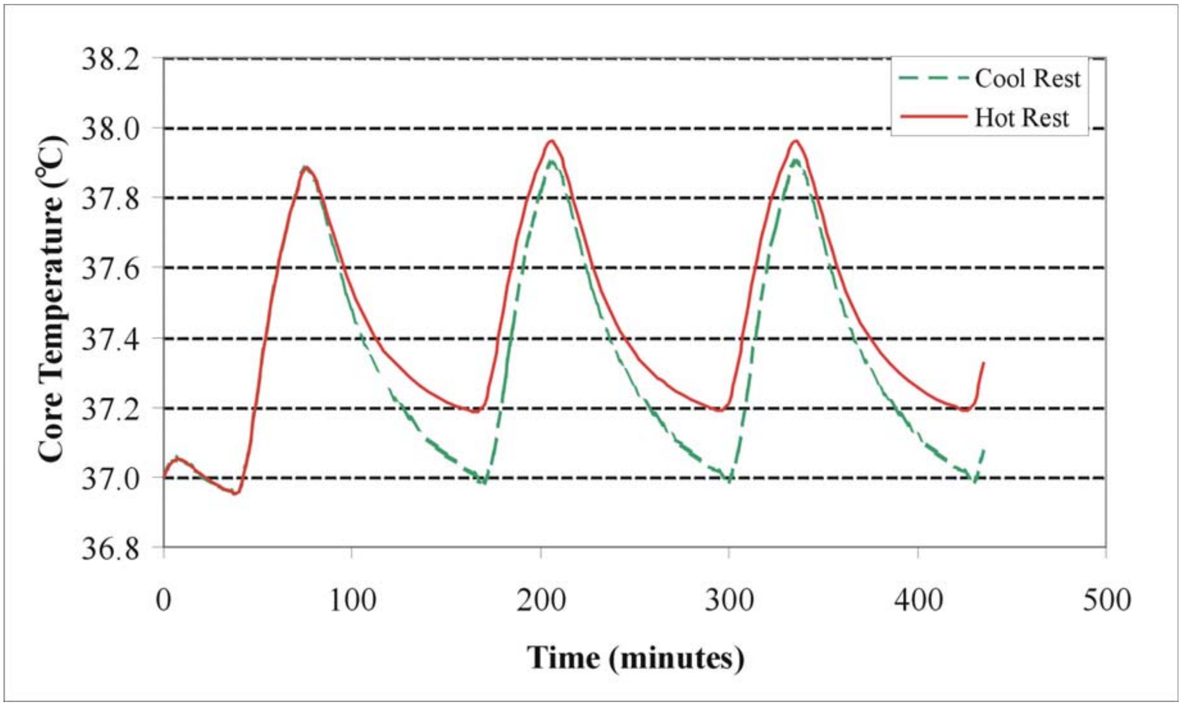

Figure 6. Example core temperature response to intermittent work where the resting conditions are either the same as the working conditions (34°C, 10% RH) or kept cool (25°C, 10% RH). The total metabolic rate was 500W. The WBGT(C) was 23 during the work phase and 18 during the rest phase in the cooled condition.

The results of the continuous work section indicate that low activity tasks (metabolic rates less than approximately 300 W) can be maintained indefinitely without exceeding the safe core temperature criterion (38°C) at least up to WBGT(C) values of 31 or 32. Although not shown explicitly in Table 7 and Table 8, this is reflected in the long work duration and small rest/work ratios in these conditions. The presence of rest intervals in these conditions is a limitation of the model implementation for intermittent work and merely reflects the selection of the levels of work duration and rest/work ratios selected for the analysis. It is expected that an optimal solution would tend to a negligibly small rest period as suggested by the continuous work analysis of the previous section.

The safe work and rest durations of this study were compared with those published in the US and CF guidelines as shown in Table 10. Each of the studies have different WBGT and work rate values so direct comparison is imprecise, but generally, the results of this study are less restrictive at low work rates and more restrictive at high work rates than the current CF guideline, and generally less restrictive than the US guideline. In the table, the green solid cells indicate continuous work is possible while the red cells with numbers are the values of the closest conditions in the published guidelines rather than recommended values. In most cases, the results of this study are sufficiently close to the published guidelines that they could be used with care and common sense as estimates of how long work and rest intervals should be for safe operations.

Another complicating factor when comparing the sets of results in Table 10 is that the criteria used for selecting the US and CF durations are not published with the tables. As discussed and shown in Table 9, several solutions may exist depending on what criteria are used to judge the relative merits of a work and rest cycle once the safe core temperature criterion is met. This could lead to marked differences in the tabulated times while maintaining safe working conditions used in industry standards. Nor is it clear whether other factors in addition to thermal strain were considered, such as

physical fatigue or the likelihood of dehydration. A rational comparison of these guidelines is not feasible without knowing the relevant criteria that underlie their development.

A separate set of simulations was run that tested a very limited number of work and rest durations at extreme WBGT values far beyond the published guidelines. The predicted work and rest schedules that permit safe work (core temperature less than 38°C for the entire simulation) under these conditions are shown in Table 11. The current analysis suggests that some measure of work can be conducted up to WBGT values well beyond published tables for health and safety, although Vasmatzidis, Schlegel, & Hancock (2002) note that simple cognitive tasks involving perception and psychomotor activity deteriorate significantly within the range of 30 to 33 WBGT(C), regardless of exposure duration. Testing this might be complicated by arousal due to expectation, particularly with short, uncommon tasks, although prolonged routine tasks may be sensitive to the strain.

Elaborations of these work and rest intervals could be used to extend Equation 1 and the results of Figure 4 to correct for transient excursions of the core temperature during the work phase. This would likely require additional information to create a plausible functional relationship such as: time on task ($t_{working}$) and the time to reach critical core temperature ($t_{critical}$) from equilibrium rest value, as well as the rest duration (t_{rest}) and the time required for recovery to desired core temperature ($t_{recovery}$). For instance, a simple modification to Equation 1 might take the form

$$T_{w\%} = \frac{f\left(\left(\frac{t_{\text{critical}} - t_{\text{working}}}{t_{\text{critical}}}\right), \left(\frac{t_{rest} - t_{\text{recovery}}}{t_{\text{recovery}}}\right)\right)}{\left(1 + \frac{MR_{work} - WL_{work}}{WL_{rest} - MR_{rest}}\right)} \qquad (1)$$

where the function $f()$ would serve to reduce the fraction of time spent working to maintain a safe core temperature during intermittent work. As the time on task approaches the critical time, or the rest time is less than the recovery time, the numerator of Equation 5 will decrease from the value 1 of Equation 1. If the working term is small and the resting term is large of Equation 5, then the expectation is that *f*() would tend to 1, as in Equation 1.

The WBGT(C) values of Table 11 and other tables in this report were calculated from primitive variables as shown in 0. At the high temperatures used in these calculations (extremes possible in NATO A3 environments), evaporation is the only mechanism of heat loss from the body, but the high humidity of some of these conditions restricts this as well, making them very dangerous and exposing workers to heat illness.

The results in Table 11 suggest that moderately heavy work can be performed for work intervals of about 10 minutes if a rest period of comparable length follows. Longer work intervals or shorter rest intervals resulted in core temperatures that exceeded the safe limits. These results are somewhat surprising, given the extreme WBGT values, and it is possible that the analysis is inadequate at these extreme conditions. The similarity of results from this study and the published guidelines give some margin of credibility to the results of Table 11, however, enough discrepancies exist to make human trials under controlled conditions at these extreme WBGT values mandatory before such results could be used in practice.

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Table 10. Comparison of published US and CF recommended work and rest durations with predicted values from this study. Values are approximate as the published WBGT index and metabolic rates differ between US and CF sources. The durations are in minutes and the ratio of the rest to work interval durations is dimensionless. The solid, green cells indicate continuous work is possible under the stated conditions. The solid red cells indicate work is not recommended; the numbers in these cells are the closest recommended values published. No corrections have been made to compensate for different WBGT or metabolic rates.

WBGT C	Interval Duration (min)	Total Metabolic Rate											
		250 W			350 W			500 W			700 W		
		US	CF	Current study	US	CF	Current study	US	CF	Current study	US	CF	Current study
~24	Work	Continuous	Work	Possible						40	40		10
	Rest									47	20		12
	R/W									1.2	0.5		1.2
~27	Work				50			30	45	30	30	30	10
	Rest				10			30	15	35	30	30	12
	R/W				0.2			1.0	0.3	1.2	1	1.0	1.2
~30	Work				30			20	30	20	20	15	10
	Rest				30			40	30	24	40	45	15
	R/W				1.0			2.0	1.0	1.2	2	3.0	1.5
~32	Work	50	15		20	15		10	15	10	10	15	10
	Rest	10	45		40	45		50	45	12	50	45	40
	R/W	0.2	3.0		2.0	3.0		5	3.0	1.2	5	3	4.0

Table 11. Work and rest durations from this study for a very limited number of factor levels with rest occurring in the same environmental conditions as work.

WBGT	Total Metabolic Rate								
	350 W			600 W			850 W		
C	Work	Rest	R/W Ratio	Work	Rest	R/W Ratio	Work	Rest	W/R Ratio
23	70	42	0.6	10	6	0.6	10	12	1.2
26	70	42	0.6	10	6	0.6	10	12	1.2
30	70	42	0.6	10	6	0.6	10	12	1.2
33	50	30	0.6	10	6	0.6	10	12	1.2
34	50	30	0.6	10	6	0.6	10	12	1.2
38	30	18	0.6	10	12	1.2	Work	not	
42	10	6	0.6	10	12	1.2	recomm	ended	
43	10	6	0.6	10	12	1.2			
47	10	6	0.6	10	12	1.2			

Lessons learned

The following list documents a number of issues that affect M&S projects in general as well as specific issues for applying M&S to the analysis of thermal strain for prediction work-rest cycles. The intent of this section is to identify obstacles that were encountered in this study and propose either means to circumvent them or at least allow for their effects in future project plans.

1) Establish broad collaborative agreements with interested partners early.

   A collaborative agreement was negotiated between DRDC Toronto and QinetiQ covering topics associated with human behaviour representation and performance. The agreement protects intellectual property rights and establishes obligations between each party. This was a necessary step before the QinetiQ thermal model could be released and used in the study.

   This process took approximately eight months for approval in principle by both parties. Then, another month was spent installing and integrating the model locally with IPME as the installation was complicated by differences between hardware and software between the two parties. Yet another month of learning how to use the model appropriately was required to ensure that the model inputs were correct and the output was what was expected. An error in the program was identified during this period, requiring a correction to the thermal model. Thus, it took approximately nine months from initial discussions to the point where the thermal model could be used effectively.

   Such delays must be considered when planning a project, particularly when they are associated with tasks on the critical path, to establish appropriate timelines. In this project, an independent development of a simpler thermal model was largely completed as a contingency, although this development was suspended upon receipt of the QinetiQ model. These contingency activities are resource intensive and could be avoided if reliable accesses to vetted models are established early in the project.

   With this collaborative agreement now in place, DRDC Toronto has a mechanism to exchange models or data with QinetiQ[14] and future exchanges should proceed more quickly. Such partnerships with industry supplement traditional agreements among governments (such as The Technical Cooperation Program) to make projects feasible.

2) Performance moderator functions such as the QinetiQ thermal physiology model take time to develop and validate.

   Development of reliable human performance and state models takes considerable understanding of the underlying science and supporting data. The Kraning heat strain model (Kraning & Gonzalez, 1997) was partially developed as a contingency plan. This model builds on years of empirical study of human thermal physiology. Implementation took several weeks work using a rather complete description from the open literature. Verification and correction of the published model against other published references took several additional weeks. In the end, the Kraning model development was suspended as the QinetiQ model was obtained, but several more weeks would have been required for testing, correcting and validation against data already gathered before it could have been used with confidence.

[14] QinetiQ, Ltd., formerly part of the UK Defence Research Evaluation and Research Agency, is a private agency, traditionally having similar defence research and development interests as DRDC.

This suggests that there should be an ongoing effort to formalize human sciences data into computational models to prevent lengthy delays, particularly in short, time sensitive projects. For each development, archival data sets will be required that can be used as standards to validate the models and serve as references that define the range of usefulness. Seldom are the results of a single experiment sufficient to allow generalization requiring several empirical studies to provide adequate data for validation and accreditation even in limited applications. The robustness of any model must be measured against various empirical approaches under varying conditions with different methods before a sense of adequacy can be established. While TTCP and NATO RTO panels have made some efforts in this regard, it is evident that more work is required to establish an encyclopaedia of human models for general use.

3) The published CF guidelines for working in hot environments do not document what criteria were used to establish them.

   For the end user of these guidelines, it may not be necessary to publish the results with the criteria to ensure appropriate use. For the administration of such publications, however, such references to the supporting studies, the criteria used in the assessment, and the assumptions made provide a wealth of information and should be documented. Without these references, comparisons of recommendations and assessment for particular applications become difficult if not impossible. Further, it makes rational extension of the guidelines difficult, possibly requiring a complete reworking of the supporting studies and documentation to provide adequate confidence that the guidelines are appropriate, leading to additional delays and cost.

4) Recommendations in the literature may be inaccurate and must be substantiated by data if they are to have credibility.

   The relationship that relates average metabolic rate, working metabolic rate, and resting metabolic rate (Equation 1) is an example of suggestions from the literature that need supporting evidence. In this instance, the suggestion may be an appropriate starting point for further study, but its application without forethought could lead to a situation that violates a number of assumptions (such as the transient nature of the core temperature response) with potential health and safety risks. Thus, recommendations in the literature should not be used without independent validation.

5) The number of factors that are of interest in human studies is large and even the number of factors that are central to a particular issue may involve too broad a range of conditions to consider human studies alone.

   In this study, only a few of the factors were considered and analysed, yet thousands of simulated experiments were conducted; too many to be done affordably in a thermal physiology laboratory with human subjects. While experimental studies must be considered an essential part of studies such as the current one, they can be conducted judiciously, selecting appropriate conditions as spot checks on the validity of the analytical predictions to save time, money and to reduce risks associated with human experiments.

6) Current publications do not provide adequate risk assessment information.

   Current industrial guidelines do not specify the risk associated with working at the recommended rates; presumably these guidelines were selected to make the risk of heat injury negligible. A risk and severity assessment should accompany guidelines to help commanders make decisions where

heat strain is not the only consideration. Data such as that compiled by USARIEM[15] may provide more insight than a guideline alone.

15 United States Army Research Institute of Environmental Medicine: for example, see Sawka and Pandolf (2001)

Recommendations and a way ahead

This study should be considered an initial reassessment of appropriate work and rest durations for hot environments. Revision of the current CF publication will require additional analytical studies involving a number of steps before new guidelines can be published with confidence.

1) The QinetiQ thermal model should be independently validated against human data from experiments in hot environments. DRDC Toronto, QinetiQ, USARIEM and similar institutions have a wealth of data that could be used for this purpose if the underlying studies are sufficiently well documented that they support representation in computational models.

2) Establish a set of evaluation criteria that are meaningful to the CF and that have appropriate scientific attributes that can be measured with sufficient sensitivity. While this may include the traditional core temperature measurement, other variables, with their corresponding impact on performance, health and safety, should be considered, such as the rate of change of core temperature, evaluating the impact of operator state on performance changes, particularly errors during military tasks that are cognitively intensive and known to belong to classes of tasks that are susceptible to heat strain.

3) Establish a standard set of assessment factors that are to be controlled (such as work rate and environmental conditions) that overlap and extend both the range of current guidelines and the results of this study. Using these conditions, validate the analytical results and assess the current guidelines at select conditions with human trials or existing data.

4) If the analytical results are found to be acceptable, conduct further simulations to optimize work and rest conditions under various environmental conditions, at various work rates. Use continuous work analyses to first estimate the acceptable average metabolic rate for untested WBGT values; use the current results for WBGT values studied to establish starting points and ranges for the analysis.

5) Assess the sensitivity of these to individual factors (such as acclimatization) or environmental variations (such as clothing properties), developing modifications to the recommend results that accommodate these factors individually.

6) Assess the most important factors in pairwise combinations analytically to see if linear corrections are adequate. If feasible, develop corrections to the continuous work values that accommodate effects of additional important factors such as core temperature transients.

7) Reconfirm the recommended work and rest durations as well as the corrections with human trials for a selection of conditions to establish confidence in the results.

8) Develop a computerized program suitable for commanders in the field that integrates meteorological data or WBGT values to determine recommend work and rest durations as well as providing risk estimates of thermal casualties and error rates for work outside of the recommended range.

Conclusion

This study shows that modelling and simulation fulfills a role that empirical studies cannot perform practicably. It also shows that some theoretical positions, such as the model of Brake and Bates, while a starting point, lack the insight that a dynamic simulation brings to the analysis. While the current analytical model did not analyze the CC130 Aircraft Technician's task performance in detail, the potential for incorporating additional aspects from the human factors task analysis into the model should be evident and could lead to a broader assessment of performance degradation during work under extreme conditions. This would lead to a further refinement of the recommended work and rest durations for operations in extreme climates.

The analytical results suggest a more liberal set of work-rest durations may be acceptable than those published in the current CF guidelines. While the current study indicates that cool resting conditions result in only modest improvement in thermal strain, the results make no statement about the psychological effects that might arise under these conditions. Thus, while little benefit of a cool resting environment was found here, that should not be considered a recommendation for eliminating such facilities. Additional study of heat strain effects on mental performance and psychological factors such as morale would be required before such a decision could be made rationally.

Further work is required to validate the QinetiQ thermal model and to examine the effect of thermal strain on mental performance before reassessing the current guidelines. Once validation of the thermal model has been conducted, the guidelines could be extended through further analytical methods to provide more accurate and useful information, allowing commanders to make better risk assessments. The collaborative agreement and integration of the QinetiQ thermal physiological model with IPME and the results of the current study provide DRDC with the analytical tools required for such a task.

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Appendix A. Continuous work results summary.

Predicted times to reach equilibrium and the resulting temperatures during continuous work at various environmental conditions. Predicted water loss rate is due to sweating and respiratory losses only and does not include other metabolic water losses.

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m²	W	°C	°C	min	min	min	min	min	L/h
21.6	30	30	0.5	0	95	37.0	35.5	75	-	-	-	-	0.1
21.6	30	30	0.5	0	350	37.7	35.0	90	-	-	-	-	0.4
21.6	30	30	0.5	0	605	38.4	35.9	115	45	-	-	-	1.0
21.6	30	30	0.5	0	865	-	-	-	30	40	55	75	1.5
21.6	30	30	0.5	0	1,120	-	-	-	25	30	40	45	1.6
22.4	30	30	0.5	100	96	37.0	35.7	75	-	-	-	-	0.1
22.4	30	30	0.5	100	350	37.8	35.3	95	-	-	-	-	0.5
22.4	30	30	0.5	100	606	38.5	36.2	125	45	110	-	-	1.2
22.4	30	30	0.5	100	865	-	-	-	30	40	55	70	1.5
22.4	30	30	0.5	100	1,121	-	-	-	25	30	35	45	1.6
23.0	30	40	0.5	0	95	37.0	35.5	65	-	-	-	-	0.1
23.0	30	40	0.5	0	350	37.8	35.0	95	-	-	-	-	0.4
23.0	30	40	0.5	0	607	38.7	36.3	145	45	90	-	-	1.3
23.0	30	40	0.5	0	866	-	-	-	30	40	50	65	1.5
23.0	30	40	0.5	0	1,122	-	-	-	25	30	35	45	1.7
23.1	30	30	0.5	200	96	37.1	35.9	75	-	-	-	-	0.1
23.1	30	30	0.5	200	350	37.8	35.5	95	-	-	-	-	0.5
23.1	30	30	0.5	200	607	38.6	36.4	135	40	85	-	-	1.3
23.1	30	30	0.5	200	866	-	-	-	30	40	50	65	1.5

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
23.1	30	30	0.5	200	1,122	-	-	-	25	30	35	45	1.7
23.8	30	30	0.5	300	97	37.1	36.1	80	-	-	-	-	0.2
23.8	30	30	0.5	300	351	37.8	35.6	95	-	-	-	-	0.6
23.8	30	30	0.5	300	608	38.8	36.6	145	40	75	-	-	1.4
23.8	30	30	0.5	300	867	-	-	-	30	40	50	65	1.6
23.8	30	30	0.5	300	1,120	-	-	-	25	30	35	40	1.6
23.8	30	40	0.5	100	96	37.0	35.7	75	-	-	-	-	0.1
23.8	30	40	0.5	100	350	37.8	35.2	95	-	-	-	-	0.5
23.8	30	40	0.5	100	608	38.8	36.5	150	40	75	-	-	1.4
23.8	30	40	0.5	100	866	-	-	-	30	40	50	60	1.5
23.8	30	40	0.5	100	1,120	-	-	-	25	30	35	40	1.6
24.4	30	50	0.5	0	95	37.0	35.4	60	-	-	-	-	0.1
24.4	30	50	0.5	0	350	37.8	35.0	95	-	-	-	-	0.4
24.4	30	50	0.5	0	610	39.0	36.7	185	40	70	170	-	1.6
24.4	30	50	0.5	0	868	-	-	-	30	40	50	60	1.5
24.4	30	50	0.5	0	1,121	-	-	-	25	30	35	40	1.6
24.6	30	40	0.5	200	96	37.1	35.9	75	-	-	-	-	0.1
24.6	30	40	0.5	200	350	37.8	35.5	95	-	-	-	-	0.5
24.6	30	40	0.5	200	609	38.9	36.7	165	40	70	-	-	1.6
24.6	30	40	0.5	200	867	-	-	-	30	40	50	60	1.5
24.6	30	40	0.5	200	1,121	-	-	-	25	30	35	40	1.6
25.2	30	50	0.5	100	96	37.1	35.7	75	-	-	-	-	0.1
25.2	30	50	0.5	100	350	37.8	35.3	95	-	-	-	-	0.5

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
25.2	30	50	0.5	100	611	39.2	37.0	205	40	65	120	-	1.8
25.2	30	50	0.5	100	867	-	-	-	30	35	45	55	1.5
25.2	30	50	0.5	100	1,122	-	-	-	25	30	35	40	1.6
25.2	30	40	0.5	300	97	37.1	36.1	80	-	-	-	-	0.2
25.2	30	40	0.5	300	351	37.9	35.6	95	-	-	-	-	0.6
25.2	30	40	0.5	300	611	39.1	37.0	190	40	65	130	-	1.8
25.2	30	40	0.5	300	867	-	-	-	30	35	45	55	1.5
25.2	30	40	0.5	300	1,122	-	-	-	25	30	35	40	1.6
25.6	35	30	0.5	0	96	37.1	35.9	75	-	-	-	-	0.1
25.6	35	30	0.5	0	350	37.8	35.4	95	-	-	-	-	0.5
25.6	35	30	0.5	0	609	38.9	36.7	160	40	70	-	-	1.6
25.6	35	30	0.5	0	867	-	-	-	30	40	50	60	1.6
25.6	35	30	0.5	0	1,121	-	-	-	25	30	35	40	1.6
25.6	30	60	0.5	0	95	37.0	35.4	55	-	-	-	-	0.1
25.6	30	60	0.5	0	350	37.8	35.1	95	-	-	-	-	0.5
25.6	30	60	0.5	0	613	-	-	-	40	60	95	170	1.6
25.6	30	60	0.5	0	869	-	-	-	30	35	45	55	1.5
25.6	30	60	0.5	0	1,124	-	-	-	25	30	35	40	1.6
25.9	30	50	0.5	200	96	37.1	35.9	75	-	-	-	-	0.1
25.9	30	50	0.5	200	351	37.8	35.5	95	-	-	-	-	0.5
25.9	30	50	0.5	200	613	-	-	-	40	60	100	245	1.8
25.9	30	50	0.5	200	868	-	-	-	30	35	45	55	1.5
25.9	30	50	0.5	200	1,123	-	-	-	25	30	35	40	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m²	W	°C	°C	min	min	min	min	min	L/h
26.4	35	30	0.5	100	97	37.1	36.1	80	-	-	-	-	0.2
26.4	35	30	0.5	100	351	37.9	35.6	95	-	-	-	-	0.6
26.4	35	30	0.5	100	611	39.1	36.9	190	40	65	130	-	1.8
26.4	35	30	0.5	100	867	-	-	-	30	35	45	55	1.5
26.4	35	30	0.5	100	1,122	-	-	-	25	30	35	40	1.6
26.5	30	60	0.5	100	96	37.1	35.7	75	-	-	-	-	0.1
26.5	30	60	0.5	100	351	37.8	35.4	100	-	-	-	-	0.5
26.5	30	60	0.5	100	614	-	-	-	40	55	85	130	1.5
26.5	30	60	0.5	100	868	-	-	-	30	35	45	50	1.5
26.5	30	60	0.5	100	1,125	-	-	-	25	30	35	40	1.7
26.6	30	50	0.5	300	97	37.1	36.1	80	-	-	-	-	0.2
26.6	30	50	0.5	300	351	37.9	35.8	100	-	-	-	-	0.6
26.6	30	50	0.5	300	614	-	-	-	40	55	85	150	1.6
26.6	30	50	0.5	300	869	-	-	-	30	35	45	55	1.6
26.6	30	50	0.5	300	1,124	-	-	-	25	30	35	40	1.7
26.8	30	70	0.5	0	95	37.0	35.4	50	-	-	-	-	0.1
26.8	30	70	0.5	0	351	37.8	35.4	105	-	-	-	-	0.5
26.8	30	70	0.5	0	615	-	-	-	40	55	75	105	1.5
26.8	30	70	0.5	0	870	-	-	-	30	35	40	50	1.5
26.8	30	70	0.5	0	1,126	-	-	-	25	30	35	40	1.7
27.1	35	30	0.5	200	97	37.2	36.2	80	-	-	-	-	0.2
27.1	35	30	0.5	200	351	37.9	35.8	95	-	-	-	-	0.6
27.1	35	30	0.5	200	612	39.3	37.1	180	40	60	100	-	2.0

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
27.1	35	30	0.5	200	868	-	-	-	30	35	45	55	1.6
27.1	35	30	0.5	200	1,123	-	-	-	25	30	35	40	1.7
27.2	30	60	0.5	200	96	37.1	35.9	75	-	-	-	-	0.1
27.2	30	60	0.5	200	351	37.9	35.7	105	-	-	-	-	0.6
27.2	30	60	0.5	200	614	-	-	-	40	55	75	110	1.5
27.2	30	60	0.5	200	869	-	-	-	30	35	45	50	1.5
27.2	30	60	0.5	200	1,126	-	-	-	25	30	35	40	1.7
27.2	35	40	0.5	0	96	37.1	35.9	75	-	-	-	-	0.1
27.2	35	40	0.5	0	351	37.9	35.5	100	-	-	-	-	0.6
27.2	35	40	0.5	0	613	-	-	-	40	60	90	165	1.6
27.2	35	40	0.5	0	869	-	-	-	30	35	45	55	1.6
27.2	35	40	0.5	0	1,124	-	-	-	25	30	35	40	1.7
27.7	30	70	0.5	100	96	37.0	35.7	70	-	-	-	-	0.1
27.7	30	70	0.5	100	351	37.9	35.8	115	-	-	-	-	0.6
27.7	30	70	0.5	100	616	-	-	-	35	50	70	95	1.5
27.7	30	70	0.5	100	871	-	-	-	30	35	40	50	1.6
27.7	30	70	0.5	100	1,123	-	-	-	25	30	35	-	1.6
27.7	35	30	0.5	300	97	37.2	36.4	80	-	-	-	-	0.2
27.7	35	30	0.5	300	352	38.0	36.1	100	175	-	-	-	0.7
27.7	35	30	0.5	300	613	-	-	-	35	55	85	160	1.7
27.7	35	30	0.5	300	867	-	-	-	30	35	45	50	1.5
27.7	35	30	0.5	300	1,124	-	-	-	25	30	35	40	1.7
27.9	30	60	0.5	300	97	37.1	36.1	80	-	-	-	-	0.2

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
27.9	30	60	0.5	300	352	38.0	36.0	105	-	-	-	-	0.7
27.9	30	60	0.5	300	615	-	-	-	35	50	70	100	1.5
27.9	30	60	0.5	300	870	-	-	-	30	35	40	50	1.6
27.9	30	60	0.5	300	1,122	-	-	-	25	30	35	-	1.6
28.0	35	40	0.5	100	97	37.1	36.1	75	-	-	-	-	0.2
28.0	35	40	0.5	100	351	37.9	35.8	100	-	-	-	-	0.6
28.0	35	40	0.5	100	614	-	-	-	35	55	80	125	1.6
28.0	35	40	0.5	100	868	-	-	-	30	35	45	50	1.5
28.0	35	40	0.5	100	1,125	-	-	-	25	30	35	40	1.7
28.4	30	70	0.5	200	96	37.1	35.9	75	-	-	-	-	0.1
28.4	30	70	0.5	200	352	38.0	36.1	120	125	-	-	-	0.7
28.4	30	70	0.5	200	616	-	-	-	35	50	65	85	1.5
28.4	30	70	0.5	200	869	-	-	-	25	35	40	45	1.5
28.4	30	70	0.5	200	1,124	-	-	-	25	30	30	35	1.6
28.7	35	40	0.5	200	97	37.2	36.2	80	-	-	-	-	0.2
28.7	35	40	0.5	200	352	38.0	36.1	105	130	-	-	-	0.7
28.7	35	40	0.5	200	614	-	-	-	35	50	75	105	1.6
28.7	35	40	0.5	200	869	-	-	-	25	35	40	50	1.6
28.7	35	40	0.5	200	1,126	-	-	-	25	30	35	40	1.7
28.8	35	50	0.5	0	96	37.1	35.9	75	-	-	-	-	0.1
28.8	35	50	0.5	0	351	37.9	35.9	110	-	-	-	-	0.6
28.8	35	50	0.5	0	615	-	-	-	35	50	70	95	1.5
28.8	35	50	0.5	0	871	-	-	-	25	35	40	50	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
28.8	35	50	0.5	0	1,123	-	-	-	25	30	35	-	1.6
29.0	30	70	0.5	300	97	37.2	36.1	80	-	-	-	-	0.2
29.0	30	70	0.5	300	353	38.1	36.4	125	90	-	-	-	0.8
29.0	30	70	0.5	300	616	-	-	-	35	50	60	80	1.5
29.0	30	70	0.5	300	870	-	-	-	25	35	40	45	1.5
29.0	30	70	0.5	300	1,124	-	-	-	25	30	30	35	1.6
29.4	35	40	0.5	300	97	37.2	36.4	80	-	-	-	-	0.2
29.4	35	40	0.5	300	352	38.0	36.3	105	90	-	-	-	0.8
29.4	35	40	0.5	300	615	-	-	-	35	50	65	90	1.5
29.4	35	40	0.5	300	871	-	-	-	25	35	40	50	1.6
29.4	35	40	0.5	300	1,123	-	-	-	25	30	35	-	1.6
29.6	40	30	0.5	0	97	37.2	36.2	80	-	-	-	-	0.2
29.6	40	30	0.5	0	352	38.0	36.1	105	140	-	-	-	0.7
29.6	40	30	0.5	0	614	-	-	-	35	50	75	110	1.6
29.6	40	30	0.5	0	869	-	-	-	25	35	40	50	1.6
29.6	40	30	0.5	0	1,126	-	-	-	25	30	35	40	1.7
29.6	35	50	0.5	100	97	37.1	36.0	75	-	-	-	-	0.2
29.6	35	50	0.5	100	352	38.0	36.2	120	105	-	-	-	0.7
29.6	35	50	0.5	100	615	-	-	-	35	50	65	85	1.5
29.6	35	50	0.5	100	869	-	-	-	25	35	40	45	1.5
29.6	35	50	0.5	100	1,124	-	-	-	25	30	30	35	1.6
30.2	35	60	0.5	0	96	37.1	35.8	75	-	-	-	-	0.1
30.2	35	60	0.5	0	353	38.2	36.5	135	85	-	-	-	0.9

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
30.2	35	60	0.5	0	617	-	-	-	35	45	60	75	1.5
30.2	35	60	0.5	0	872	-	-	-	25	35	40	45	1.6
30.2	35	60	0.5	0	1,126	-	-	-	25	30	30	35	1.7
30.3	35	50	0.5	200	97	37.2	36.2	80	-	-	-	-	0.2
30.3	35	50	0.5	200	353	38.1	36.5	130	80	-	-	-	0.9
30.3	35	50	0.5	200	616	-	-	-	35	45	60	80	1.5
30.3	35	50	0.5	200	870	-	-	-	25	35	40	45	1.6
30.3	35	50	0.5	200	1,124	-	-	-	25	30	30	35	1.6
30.3	40	30	0.5	100	97	37.2	36.3	80	-	-	-	-	0.2
30.3	40	30	0.5	100	352	38.0	36.3	105	90	-	-	-	0.8
30.3	40	30	0.5	100	615	-	-	-	35	50	65	95	1.6
30.3	40	30	0.5	100	871	-	-	-	25	35	40	50	1.6
30.3	40	30	0.5	100	1,123	-	-	-	25	30	30	35	1.6
30.9	35	50	0.5	300	97	37.2	36.3	80	-	-	-	-	0.2
30.9	35	50	0.5	300	354	38.3	36.8	140	70	-	-	-	1.0
30.9	35	50	0.5	300	616	-	-	-	35	45	55	70	1.5
30.9	35	50	0.5	300	872	-	-	-	25	35	40	45	1.6
30.9	35	50	0.5	300	1,125	-	-	-	25	30	30	35	1.7
31.0	35	60	0.5	100	97	37.1	36.0	75	-	-	-	-	0.2
31.0	35	60	0.5	100	355	38.3	36.7	155	70	-	-	-	1.0
31.0	35	60	0.5	100	617	-	-	-	35	45	55	70	1.5
31.0	35	60	0.5	100	873	-	-	-	25	30	40	45	1.6
31.0	35	60	0.5	100	1,127	-	-	-	25	30	30	35	1.7

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
31.0	40	30	0.5	200	98	37.3	36.5	85	-	-	-	-	0.3
31.0	40	30	0.5	200	353	38.1	36.5	115	75	-	-	-	0.9
31.0	40	30	0.5	200	616	-	-	-	35	45	60	85	1.6
31.0	40	30	0.5	200	869	-	-	-	25	35	40	45	1.6
31.0	40	30	0.5	200	1,124	-	-	-	25	30	30	35	1.7
31.5	40	40	0.5	0	97	37.2	36.2	80	-	-	-	-	0.2
31.5	40	40	0.5	0	354	38.2	36.6	135	75	-	-	-	0.9
31.5	40	40	0.5	0	616	-	-	-	35	45	60	75	1.5
31.5	40	40	0.5	0	871	-	-	-	25	35	40	45	1.6
31.5	40	40	0.5	0	1,125	-	-	-	25	30	30	35	1.7
31.5	35	70	0.5	0	96	37.1	35.8	75	-	-	-	-	0.1
31.5	35	70	0.5	0	360	39.0	37.6	300	65	120	310	-	1.6
31.5	35	70	0.5	0	618	-	-	-	35	40	50	60	1.4
31.5	35	70	0.5	0	872	-	-	-	25	30	35	40	1.5
31.5	35	70	0.5	0	1,129	-	-	-	20	25	30	35	1.7
31.7	40	30	0.5	300	98	37.3	36.6	85	-	-	-	-	0.3
31.7	40	30	0.5	300	354	38.2	36.8	125	65	-	-	-	1.0
31.7	40	30	0.5	300	616	-	-	-	35	45	60	75	1.5
31.7	40	30	0.5	300	870	-	-	-	25	35	40	45	1.6
31.7	40	30	0.5	300	1,125	-	-	-	25	30	30	35	1.7
31.7	35	60	0.5	200	97	37.2	36.2	80	-	-	-	-	0.2
31.7	35	60	0.5	200	357	38.5	37.1	190	65	160	-	-	1.3
31.7	35	60	0.5	200	618	-	-	-	35	45	55	65	1.5

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
31.7	35	60	0.5	200	874	-	-	-	25	30	35	45	1.6
31.7	35	60	0.5	200	1,128	-	-	-	25	30	30	35	1.7
32.3	40	40	0.5	100	97	37.2	36.3	80	-	-	-	-	0.2
32.3	40	40	0.5	100	355	38.3	36.9	145	65	-	-	-	1.1
32.3	40	40	0.5	100	617	-	-	-	35	45	55	70	1.5
32.3	40	40	0.5	100	872	-	-	-	25	30	40	45	1.6
32.3	40	40	0.5	100	1,126	-	-	-	25	30	30	35	1.7
32.3	35	70	0.5	100	97	37.1	36.0	75	-	-	-	-	0.2
32.3	35	70	0.5	100	364	39.4	38.0	335	60	100	170	525	1.9
32.3	35	70	0.5	100	619	-	-	-	35	40	50	60	1.5
32.3	35	70	0.5	100	873	-	-	-	25	30	35	40	1.6
32.3	35	70	0.5	100	1,130	-	-	-	20	25	30	35	1.7
32.4	35	60	0.5	300	97	37.2	36.3	80	-	-	-	-	0.2
32.4	35	60	0.5	300	360	38.9	37.5	245	55	105	490	-	1.6
32.4	35	60	0.5	300	618	-	-	-	35	40	50	60	1.5
32.4	35	60	0.5	300	872	-	-	-	25	30	35	40	1.6
32.4	35	60	0.5	300	1,129	-	-	-	20	25	30	35	1.7
32.9	40	40	0.5	200	98	37.3	36.5	85	-	-	-	-	0.3
32.9	40	40	0.5	200	357	38.6	37.1	175	60	145	-	-	1.3
32.9	40	40	0.5	200	617	-	-	-	35	40	55	65	1.5
32.9	40	40	0.5	200	874	-	-	-	25	30	35	45	1.7
32.9	40	40	0.5	200	1,127	-	-	-	25	30	30	35	1.7
33.0	35	70	0.5	200	97	37.2	36.2	80	-	-	-	-	0.2

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
33.0	35	70	0.5	200	364	-	-	-	55	85	125	205	1.6
33.0	35	70	0.5	200	619	-	-	-	30	40	50	55	1.5
33.0	35	70	0.5	200	874	-	-	-	25	30	35	40	1.6
33.0	35	70	0.5	200	1,131	-	-	-	20	25	30	35	1.8
33.2	40	50	0.5	0	97	37.2	36.2	80	-	-	-	-	0.2
33.2	40	50	0.5	0	361	39.1	37.6	275	60	105	240	-	1.7
33.2	40	50	0.5	0	618	-	-	-	30	40	50	60	1.5
33.2	40	50	0.5	0	872	-	-	-	25	30	35	40	1.6
33.2	40	50	0.5	0	1,130	-	-	-	20	25	30	35	1.7
33.6	45	30	0.5	0	98	37.3	36.4	80	-	-	-	-	0.3
33.6	45	30	0.5	0	356	38.5	37.0	155	60	210	-	-	1.2
33.6	45	30	0.5	0	617	-	-	-	35	45	55	65	1.5
33.6	45	30	0.5	0	873	-	-	-	25	30	35	45	1.7
33.6	45	30	0.5	0	1,127	-	-	-	25	30	30	35	1.7
33.6	40	40	0.5	300	98	37.3	36.6	85	-	-	-	-	0.3
33.6	40	40	0.5	300	359	38.8	37.3	190	55	100	-	-	1.5
33.6	40	40	0.5	300	617	-	-	-	30	40	50	60	1.5
33.6	40	40	0.5	300	871	-	-	-	25	30	35	40	1.6
33.6	40	40	0.5	300	1,128	-	-	-	20	25	30	35	1.8
33.7	35	70	0.5	300	97	37.3	36.3	85	-	-	-	-	0.3
33.7	35	70	0.5	300	365	-	-	-	50	75	105	145	1.5
33.7	35	70	0.5	300	620	-	-	-	30	40	45	55	1.5
33.7	35	70	0.5	300	875	-	-	-	25	30	35	40	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
33.7	35	70	0.5	300	1,132	-	-	-	20	25	30	35	1.8
34.0	40	50	0.5	100	97	37.2	36.3	80	-	-	-	-	0.3
34.0	40	50	0.5	100	364	-	-	-	55	85	140	280	1.7
34.0	40	50	0.5	100	618	-	-	-	30	40	50	55	1.5
34.0	40	50	0.5	100	873	-	-	-	25	30	35	40	1.6
34.0	40	50	0.5	100	1,131	-	-	-	20	25	30	35	1.8
34.4	45	30	0.5	100	98	37.3	36.6	85	-	-	-	-	0.3
34.4	45	30	0.5	100	358	38.7	37.2	160	55	110	-	-	1.4
34.4	45	30	0.5	100	618	-	-	-	30	40	50	65	1.6
34.4	45	30	0.5	100	871	-	-	-	25	30	35	40	1.6
34.4	45	30	0.5	100	1,128	-	-	-	20	25	30	35	1.7
34.7	40	50	0.5	200	98	37.3	36.4	85	-	-	-	-	0.3
34.7	40	50	0.5	200	364	-	-	-	50	75	110	170	1.6
34.7	40	50	0.5	200	619	-	-	-	30	40	45	55	1.5
34.7	40	50	0.5	200	875	-	-	-	25	30	35	40	1.6
34.7	40	50	0.5	200	1,132	-	-	-	20	25	30	35	1.8
34.8	40	60	0.5	0	97	37.2	36.2	80	-	-	-	-	0.2
34.8	40	60	0.5	0	366	-	-	-	50	65	90	120	1.5
34.8	40	60	0.5	0	620	-	-	-	30	40	45	50	1.5
34.8	40	60	0.5	0	877	-	-	-	25	30	35	40	1.7
34.8	40	60	0.5	0	1,127	-	-	-	20	25	30	-	1.6
35.0	45	30	0.5	200	98	37.4	36.6	85	-	-	-	-	0.4
35.0	45	30	0.5	200	360	39.0	37.5	220	50	90	280	-	1.7

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
35.0	45	30	0.5	200	618	-	-	-	30	40	50	60	1.6
35.0	45	30	0.5	200	872	-	-	-	25	30	35	40	1.6
35.0	45	30	0.5	200	1,129	-	-	-	20	25	30	35	1.8
35.3	40	50	0.5	300	98	37.3	36.6	90	-	-	-	-	0.4
35.3	40	50	0.5	300	365	-	-	-	45	70	95	130	1.5
35.3	40	50	0.5	300	621	-	-	-	30	40	45	55	1.6
35.3	40	50	0.5	300	876	-	-	-	25	30	35	40	1.7
35.3	40	50	0.5	300	1,126	-	-	-	20	25	30	-	1.6
35.6	40	60	0.5	100	98	37.3	36.4	90	-	-	-	-	0.3
35.6	40	60	0.5	100	366	-	-	-	45	60	80	105	1.5
35.6	40	60	0.5	100	621	-	-	-	30	35	45	50	1.5
35.6	40	60	0.5	100	878	-	-	-	25	30	35	40	1.7
35.6	40	60	0.5	100	1,128	-	-	-	20	25	30	-	1.7
35.7	45	30	0.5	300	99	37.4	36.7	85	-	-	-	-	0.4
35.7	45	30	0.5	300	362	39.2	37.8	220	50	75	140	-	2.0
35.7	45	30	0.5	300	618	-	-	-	30	40	50	55	1.5
35.7	45	30	0.5	300	873	-	-	-	25	30	35	40	1.7
35.7	45	30	0.5	300	1,130	-	-	-	20	25	30	35	1.8
35.7	45	40	0.5	0	98	37.3	36.4	85	-	-	-	-	0.3
35.7	45	40	0.5	0	365	-	-	-	50	70	100	145	1.6
35.7	45	40	0.5	0	620	-	-	-	30	40	45	55	1.6
35.7	45	40	0.5	0	876	-	-	-	25	30	35	40	1.7
35.7	45	40	0.5	0	1,126	-	-	-	20	25	30	-	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
36.2	40	70	0.5	0	99	37.4	36.6	155	-	-	-	-	0.4
36.2	40	70	0.5	0	367	-	-	-	40	55	65	80	1.5
36.2	40	70	0.5	0	622	-	-	-	30	35	40	45	1.5
36.2	40	70	0.5	0	876	-	-	-	25	30	30	35	1.6
36.2	40	70	0.5	0	1,131	-	-	-	20	25	30	-	1.7
36.3	40	60	0.5	200	99	37.4	36.6	100	-	-	-	-	0.4
36.3	40	60	0.5	200	366	-	-	-	45	60	75	90	1.5
36.3	40	60	0.5	200	622	-	-	-	30	35	40	50	1.6
36.3	40	60	0.5	200	874	-	-	-	25	30	35	-	1.6
36.3	40	60	0.5	200	1,129	-	-	-	20	25	30	-	1.7
36.5	45	40	0.5	100	98	37.4	36.6	90	-	-	-	-	0.4
36.5	45	40	0.5	100	365	-	-	-	45	65	90	120	1.5
36.5	45	40	0.5	100	619	-	-	-	30	35	45	50	1.5
36.5	45	40	0.5	100	877	-	-	-	25	30	35	40	1.7
36.5	45	40	0.5	100	1,127	-	-	-	20	25	30	-	1.7
36.9	40	60	0.5	300	100	37.5	36.9	135	-	-	-	-	0.5
36.9	40	60	0.5	300	367	-	-	-	40	55	70	85	1.5
36.9	40	60	0.5	300	621	-	-	-	30	35	40	45	1.5
36.9	40	60	0.5	300	875	-	-	-	25	30	35	-	1.6
36.9	40	60	0.5	300	1,130	-	-	-	20	25	30	-	1.7
37.0	40	70	0.5	100	101	37.7	37.1	210	-	-	-	-	0.7
37.0	40	70	0.5	100	368	-	-	-	40	50	60	75	1.5
37.0	40	70	0.5	100	623	-	-	-	30	35	40	45	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
37.0	40	70	0.5	100	877	-	-	-	25	30	30	35	1.7
37.0	40	70	0.5	100	1,132	-	-	-	20	25	30	-	1.7
37.2	45	40	0.5	200	99	37.4	36.8	95	-	-	-	-	0.4
37.2	45	40	0.5	200	366	-	-	-	45	60	80	105	1.5
37.2	45	40	0.5	200	621	-	-	-	30	35	45	50	1.6
37.2	45	40	0.5	200	878	-	-	-	25	30	35	40	1.7
37.2	45	40	0.5	200	1,128	-	-	-	20	25	30	-	1.7
37.6	50	30	0.5	0	99	37.4	36.7	95	-	-	-	-	0.4
37.6	50	30	0.5	0	365	-	-	-	45	65	85	115	1.5
37.6	50	30	0.5	0	620	-	-	-	30	35	45	50	1.5
37.6	50	30	0.5	0	877	-	-	-	25	30	35	40	1.7
37.6	50	30	0.5	0	1,127	-	-	-	20	25	30	-	1.7
37.7	45	50	0.5	0	100	37.5	36.8	140	-	-	-	-	0.5
37.7	45	50	0.5	0	367	-	-	-	40	55	65	80	1.5
37.7	45	50	0.5	0	622	-	-	-	30	35	40	45	1.5
37.7	45	50	0.5	0	876	-	-	-	25	30	30	35	1.6
37.7	45	50	0.5	0	1,131	-	-	-	20	25	30	-	1.7
37.7	40	70	0.5	200	105	38.2	37.6	275	190	-	-	-	1.1
37.7	40	70	0.5	200	369	-	-	-	40	50	60	70	1.5
37.7	40	70	0.5	200	624	-	-	-	30	35	40	45	1.6
37.7	40	70	0.5	200	878	-	-	-	25	30	30	35	1.7
37.7	40	70	0.5	200	1,133	-	-	-	20	25	30	-	1.8
37.8	45	40	0.5	300	100	37.5	36.9	100	-	-	-	-	0.5

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
37.8	45	40	0.5	300	367	-	-	-	40	55	75	95	1.6
37.8	45	40	0.5	300	622	-	-	-	30	35	40	50	1.6
37.8	45	40	0.5	300	874	-	-	-	25	30	35	-	1.6
37.8	45	40	0.5	300	1,129	-	-	-	20	25	30	-	1.7
38.4	40	70	0.5	300	109	38.8	38.3	360	120	225	-	-	1.5
38.4	40	70	0.5	300	369	-	-	-	40	45	55	65	1.5
38.4	40	70	0.5	300	626	-	-	-	30	35	40	45	1.7
38.4	40	70	0.5	300	879	-	-	-	25	30	30	35	1.7
38.4	40	70	0.5	300	1,134	-	-	-	20	25	30	-	1.8
38.4	50	30	0.5	100	100	37.5	36.9	100	-	-	-	-	0.5
38.4	50	30	0.5	100	366	-	-	-	45	60	80	100	1.5
38.4	50	30	0.5	100	621	-	-	-	30	35	45	50	1.6
38.4	50	30	0.5	100	873	-	-	-	25	30	35	-	1.6
38.4	50	30	0.5	100	1,128	-	-	-	20	25	30	-	1.7
38.4	45	50	0.5	100	101	37.7	37.1	170	-	-	-	-	0.7
38.4	45	50	0.5	100	368	-	-	-	40	50	60	75	1.5
38.4	45	50	0.5	100	623	-	-	-	30	35	40	45	1.6
38.4	45	50	0.5	100	877	-	-	-	25	30	30	35	1.7
38.4	45	50	0.5	100	1,132	-	-	-	20	25	30	-	1.7
39.1	50	30	0.5	200	100	37.6	37.1	110	-	-	-	-	0.6
39.1	50	30	0.5	200	366	-	-	-	40	55	70	90	1.6
39.1	50	30	0.5	200	623	-	-	-	30	35	40	50	1.6
39.1	50	30	0.5	200	874	-	-	-	25	30	35	-	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
39.1	50	30	0.5	200	1,129	-	-	-	20	25	30	-	1.7
39.1	45	50	0.5	200	104	38.1	37.6	260	200	-	-	-	1.0
39.1	45	50	0.5	200	369	-	-	-	40	50	60	70	1.5
39.1	45	50	0.5	200	624	-	-	-	30	35	40	45	1.6
39.1	45	50	0.5	200	878	-	-	-	25	30	30	35	1.7
39.1	45	50	0.5	200	1,133	-	-	-	20	25	30	-	1.8
39.4	45	60	0.5	0	114	-	-	-	90	130	200	365	1.8
39.4	45	60	0.5	0	370	-	-	-	35	45	55	60	1.5
39.4	45	60	0.5	0	624	-	-	-	25	30	35	40	1.6
39.4	45	60	0.5	0	882	-	-	-	25	30	30	35	1.8
39.4	45	60	0.5	0	1,136	-	-	-	20	25	30	-	1.8
39.7	50	30	0.5	300	101	37.7	37.3	140	-	-	-	-	0.7
39.7	50	30	0.5	300	366	-	-	-	40	50	65	80	1.5
39.7	50	30	0.5	300	621	-	-	-	30	35	40	45	1.6
39.7	50	30	0.5	300	875	-	-	-	25	30	30	35	1.7
39.7	50	30	0.5	300	1,130	-	-	-	20	25	30	-	1.8
39.7	45	50	0.5	300	108	38.6	38.1	330	115	260	-	-	1.5
39.7	45	50	0.5	300	369	-	-	-	35	45	55	65	1.5
39.7	45	50	0.5	300	626	-	-	-	30	35	40	45	1.7
39.7	45	50	0.5	300	879	-	-	-	25	30	30	35	1.7
39.7	45	50	0.5	300	1,133	-	-	-	20	25	30	-	1.8
40.0	50	40	0.5	0	106	38.3	37.8	290	155	-	-	-	1.2
40.0	50	40	0.5	0	369	-	-	-	40	45	55	70	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
40.0	50	40	0.5	0	625	-	-	-	30	35	40	45	1.7
40.0	50	40	0.5	0	879	-	-	-	25	30	30	35	1.7
40.0	50	40	0.5	0	1,133	-	-	-	20	25	30	-	1.8
40.2	45	60	0.5	100	115	-	-	-	75	105	145	205	1.6
40.2	45	60	0.5	100	371	-	-	-	35	45	50	60	1.6
40.2	45	60	0.5	100	625	-	-	-	25	30	35	40	1.6
40.2	45	60	0.5	100	883	-	-	-	25	30	30	35	1.8
40.2	45	60	0.5	100	1,137	-	-	-	20	25	30	-	1.8
40.8	50	40	0.5	100	109	38.8	38.3	325	105	195	-	-	1.6
40.8	50	40	0.5	100	370	-	-	-	35	45	55	65	1.6
40.8	50	40	0.5	100	622	-	-	-	25	35	35	40	1.6
40.8	50	40	0.5	100	880	-	-	-	25	30	30	35	1.7
40.8	50	40	0.5	100	1,134	-	-	-	20	25	30	-	1.8
40.8	45	60	0.5	200	115	-	-	-	65	90	120	155	1.6
40.8	45	60	0.5	200	371	-	-	-	35	40	50	55	1.5
40.8	45	60	0.5	200	626	-	-	-	25	30	35	40	1.7
40.8	45	60	0.5	200	884	-	-	-	25	30	30	35	1.8
40.8	45	60	0.5	200	1,138	-	-	-	20	25	30	-	1.9
41.0	45	70	0.5	0	117	-	-	-	55	70	85	105	1.5
41.0	45	70	0.5	0	372	-	-	-	35	40	45	50	1.5
41.0	45	70	0.5	0	630	-	-	-	25	30	35	40	1.7
41.0	45	70	0.5	0	880	-	-	-	20	25	30	-	1.7
41.0	45	70	0.5	0	1,141	-	-	-	20	25	30	-	1.9

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
41.4	50	40	0.5	200	114	39.3	38.8	365	85	135	220	-	2.1
41.4	50	40	0.5	200	369	-	-	-	35	45	50	60	1.5
41.4	50	40	0.5	200	624	-	-	-	25	30	35	40	1.6
41.4	50	40	0.5	200	881	-	-	-	25	30	30	35	1.8
41.4	50	40	0.5	200	1,135	-	-	-	20	25	30	-	1.8
41.5	45	60	0.5	300	116	-	-	-	60	80	100	130	1.6
41.5	45	60	0.5	300	372	-	-	-	35	40	45	55	1.6
41.5	45	60	0.5	300	628	-	-	-	25	30	35	40	1.7
41.5	45	60	0.5	300	878	-	-	-	25	30	-	-	1.7
41.5	45	60	0.5	300	1,139	-	-	-	20	25	30	-	1.9
41.7	45	70	0.5	100	118	-	-	-	50	65	80	95	1.6
41.7	45	70	0.5	100	374	-	-	-	30	40	45	50	1.6
41.7	45	70	0.5	100	626	-	-	-	25	30	35	-	1.6
41.7	45	70	0.5	100	881	-	-	-	20	25	30	-	1.7
41.7	45	70	0.5	100	1,142	-	-	-	20	25	30	-	1.9
42.1	50	40	0.5	300	115	-	-	-	70	105	155	235	1.7
42.1	50	40	0.5	300	371	-	-	-	35	40	50	60	1.6
42.1	50	40	0.5	300	625	-	-	-	25	30	35	40	1.6
42.1	50	40	0.5	300	882	-	-	-	25	30	30	35	1.8
42.1	50	40	0.5	300	1,136	-	-	-	20	25	30	-	1.9
42.1	50	50	0.5	0	117	-	-	-	60	75	95	120	1.6
42.1	50	50	0.5	0	374	-	-	-	35	40	45	55	1.6
42.1	50	50	0.5	0	629	-	-	-	25	30	35	40	1.7

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
42.1	50	50	0.5	0	879	-	-	-	20	25	30	-	1.7
42.1	50	50	0.5	0	1,140	-	-	-	20	25	30	-	1.9
42.4	45	70	0.5	200	118	-	-	-	45	60	70	85	1.6
42.4	45	70	0.5	200	375	-	-	-	30	35	40	50	1.7
42.4	45	70	0.5	200	627	-	-	-	25	30	35	-	1.7
42.4	45	70	0.5	200	882	-	-	-	20	25	30	-	1.7
42.4	45	70	0.5	200	1,143	-	-	-	20	25	30	-	1.9
42.9	50	50	0.5	100	117	-	-	-	55	70	85	105	1.6
42.9	50	50	0.5	100	372	-	-	-	30	40	45	50	1.6
42.9	50	50	0.5	100	630	-	-	-	25	30	35	40	1.8
42.9	50	50	0.5	100	880	-	-	-	20	25	30	-	1.7
42.9	50	50	0.5	100	1,141	-	-	-	20	25	30	-	1.9
43.1	45	70	0.5	300	119	-	-	-	45	55	65	80	1.6
43.1	45	70	0.5	300	373	-	-	-	30	35	40	45	1.6
43.1	45	70	0.5	300	628	-	-	-	25	30	30	35	1.7
43.1	45	70	0.5	300	883	-	-	-	20	25	30	-	1.8
43.1	45	70	0.5	300	1,133	-	-	-	-	-	-	-	1.7
43.5	50	50	0.5	200	118	-	-	-	50	65	75	95	1.6
43.5	50	50	0.5	200	374	-	-	-	30	35	45	50	1.6
43.5	50	50	0.5	200	626	-	-	-	25	30	35	-	1.6
43.5	50	50	0.5	200	881	-	-	-	20	25	30	-	1.7
43.5	50	50	0.5	200	1,142	-	-	-	20	25	30	-	1.9
44.0	50	60	0.5	0	120	-	-	-	45	55	65	75	1.6

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
44.0	50	60	0.5	0	375	-	-	-	30	35	40	45	1.6
44.0	50	60	0.5	0	630	-	-	-	25	30	30	35	1.7
44.0	50	60	0.5	0	885	-	-	-	20	25	30	-	1.8
44.0	50	60	0.5	0	1,135	-	-	-	-	-	-	-	1.7
44.2	50	50	0.5	300	118	-	-	-	45	60	70	85	1.6
44.2	50	50	0.5	300	375	-	-	-	30	35	40	50	1.7
44.2	50	50	0.5	300	627	-	-	-	25	30	35	-	1.7
44.2	50	50	0.5	300	882	-	-	-	20	25	30	-	1.8
44.2	50	50	0.5	300	1,143	-	-	-	20	25	30	-	2.0
44.8	50	60	0.5	100	121	-	-	-	40	50	60	70	1.6
44.8	50	60	0.5	100	377	-	-	-	30	35	40	45	1.7
44.8	50	60	0.5	100	631	-	-	-	25	30	30	35	1.8
44.8	50	60	0.5	100	886	-	-	-	20	25	30	-	1.8
44.8	50	60	0.5	100	1,136	-	-	-	-	-	-	-	1.8
45.4	50	60	0.5	200	121	-	-	-	40	50	55	65	1.6
45.4	50	60	0.5	200	378	-	-	-	30	35	40	45	1.7
45.4	50	60	0.5	200	633	-	-	-	25	30	30	35	1.8
45.4	50	60	0.5	200	887	-	-	-	20	25	30	-	1.8
45.4	50	60	0.5	200	1,137	-	-	-	-	-	-	-	1.8
45.7	50	70	0.5	0	122	-	-	-	45	55	65	75	1.6
45.7	50	70	0.5	0	378	-	-	-	30	35	40	45	1.7
45.7	50	70	0.5	0	633	-	-	-	25	30	30	35	1.7
45.7	50	70	0.5	0	888	-	-	-	20	25	30	-	1.8

WBGT	Dry Bulb Temperature	Relative Humidity	Wind Speed	Solar Load	Total Metabolic Rate	Equilibrium Core Temperature	Equilibrium Skin Temperature	Equilibration time	Time to reach core temperature				Water Loss Rate
									38°C	38.5°C	39°C	39.5°C	
C	°C	%	m/s	W/m^2	W	°C	°C	min	min	min	min	min	L/h
45.7	50	70	0.5	0	1,138	-	-	-	-	-	-	-	1.8
46.1	50	60	0.5	300	121	-	-	-	40	45	55	60	1.7
46.1	50	60	0.5	300	375	-	-	-	30	35	35	40	1.7
46.1	50	60	0.5	300	634	-	-	-	25	30	30	35	1.8
46.1	50	60	0.5	300	888	-	-	-	20	25	30	-	1.9
46.1	50	60	0.5	300	1,137	-	-	-	-	-	-	-	1.8
46.5	50	70	0.5	100	120	-	-	-	40	50	60	65	1.6
46.5	50	70	0.5	100	380	-	-	-	30	35	40	45	1.7
46.5	50	70	0.5	100	635	-	-	-	25	30	30	35	1.8
46.5	50	70	0.5	100	890	-	-	-	20	25	30	-	1.9
46.5	50	70	0.5	100	1,139	-	-	-	-	-	-	-	1.8
47.1	50	70	0.5	200	124	-	-	-	40	45	55	65	1.7
47.1	50	70	0.5	200	376	-	-	-	30	35	40	-	1.6
47.1	50	70	0.5	200	636	-	-	-	25	30	30	35	1.8
47.1	50	70	0.5	200	891	-	-	-	20	25	30	-	1.9
47.1	50	70	0.5	200	1,140	-	-	-	-	-	-	-	1.8
47.8	50	70	0.5	300	124	-	-	-	35	45	50	60	1.7
47.8	50	70	0.5	300	378	-	-	-	30	35	35	40	1.7
47.8	50	70	0.5	300	638	-	-	-	25	30	30	35	1.9
47.8	50	70	0.5	300	892	-	-	-	20	25	30	-	1.9
47.8	50	70	0.5	300	1,141	-	-	-	-	-	-	-	1.9

Appendix B. WBGT values and corresponding environmental primitives

This table contains many of the WBGT values reported in this study and the environmental variable values used that gave rise to the WBGT. In some cases, several sets of environmental primitives gave rise to similar WBGT values. The accuracy of these WBGT values is approximately ±0.5C.

WBGT	Dry Bulb Temperature	Relative Humidity	Solar Radiation	Wind Speed
C	°C	%	W/m²	m/s
23	35	10	0	0.5
26	40	10	0	0.5
30	45	10	0	0.5
30	45	10	100	0.5
30	40	10	500	0.5
33	50	10	0	0.5
33	45	10	500	0.5
33	35	10	500	0.5
34	40	50	0	0.5
34	50	10	100	0.5
34	50	10	200	0.5
38	40	75	0	0.5
42	45	75	0	0.5
43	50	50	0	0.5
47	50	75	0	0.5

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A preliminary study of heat strain using modelling and simulation (U)
Étude préliminaire sur la fatigue due à la chaleur à l'aide de la modélisation et simulation

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